Numerical Simulation of Biomass Burning Aerosol Transport for Northern Thailand

Nurzahziani

A Thesis Submitted in Fulfillment of the Requirements for the Degree of Master of Science in Earth System Science

Prince of Songkla University

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Major Program	Earth System Science

Major Advisor

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I hereby certify that this work has not been accepted in substance for any degree, and is not being currently submitted in candidature for any degree.

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ABSTRACT

We simulated a numerical of biomass burning aerosol transport for the year 2014 and 2015 in northern Thailand using the Weather Research and Forecasting model coupled with chemistry (WRF/Chem). The global gridded analyses from the NCEP FNL (Final), the global emission data from the REanalysis of the TROpospheric chemical composition over the past 40 years (RETRO) and the Emission Database for Global Atmospheric Research (EDGAR) and the daily biomass burning emission data from 3BEM were used in this study. The simulated daily averaged particulate matters with diameters less than 10 micron (PM10) at 5-km resolution covering the 3-month period of February–April of the year 2014 and 2015 were evaluated using measurements from 13 ground stations distributed in northern Thailand. Results show PM10 concentrations from the end of February to the middle of March at most stations are relatively high and exceed the value of 50 $\mu g/m^3$, which is a threshold for polluted air quality according to the World Health Organization (WHO). We can also see that the numerical biomass burning aerosol transport simulation system can predict the times when daily averaged PM10 dry mass concentrations are high and low well for both hourly and daily comparison. The results indicated that daily simulated performed better than hourly simulated compared to ground-based measurement. The overall correlation coefficients between the daily simulations and observations for the year 2014 and 2015 are 0.7469 and 0.7751, respectively.

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Nurzahziani

CONTENTS

CONTENTS (cont.)

LIST OF FIGURES

LIST OF FIGURES (cont.)

LIST OF TABLES

CHAPTER 1
INTRODUCTION

1.1 Statement of the problem

In the Southeast Asia (SEA), open biomass burning is a main concern associated to agricultural activities (Phairuang, *et al*., 2016), such as clearing land for a new rice planting season (Duc, 2016). Biomass burning produces smoke and haze containing atmospheric particulate matters or aerosols and trace gases (Orueta, A. P., 2005; Paugam, 2015). The aerosols act as sources of pollution that tends to be found particularly in air that is nearest to the ground (Skinner, B. J., and Murck, B., 1928; Paugam, 2015). They can attack human health and have important consequences for the environment (Wiwaningkit, 2008; Kanabkawe, 2013; Huang, *et al*., 2013; Zhong, M., *et al*., 2016).

As one of agricultural-based country in SEA, Thailand generates massive amounts of agricultural waste and the economic contribution of agriculture which resulting in high concentrations of air pollutants (Kasem and Thapa, 2012). In northern Thailand, Particulate matter is the most influential air pollutant emitted from biomass burning in agricultural activities and forest fires, and it has a significant effect on air quality in this area especially during the dry season when most farmers try to clear and fertilize land before planting (Wiwaningkit, 2008; Amnauylawjarurn, 2010; Kanabkawe, 2013; Phairuang, 2016).

There are some methods that can be used to analyse and present air quality data. Measurements of air quality properties from monitoring stations are quite good for characterization of the concentration of a given pollutant at a given time and location, but still limited by their spatial distribution. This infrequent may cause unreliability for warning information. Sooktawee, *et al.*, (2015) presented the application of the calendar-style technique to visualize the 24-hour average concentration of particulate matters with diameter less than or equal to 10 microns in size (PM10) observed by the Pollution Control Department (PCD) in northern Thailand

from 2009 until 2014. In this area, heavy smoke occurs most often during March to early April. Besides that, Kanabkaew (2013) studied satellite remote sensing which is a promising technology for monitoring air quality at surface level. Satellite detectors allow us to expand the set of aerosol data. Satellites provide the true global perspective to understand how aerosols affect Earth's atmosphere and climate. This research investigated particulate matter concentration in Chiang Mai province in northern Thailand using the satellite data. In this study, the hourly particulate matter data were collected from PCD while the aerosol optical depth (AOD) data was identified by MODerate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite. To identify the relationship between AOD retrieved from MODIS and ground PM during the 2012 haze occurrence in Chiang Mai, this study used the simple linear regression and multiple linear regression.

To better understand the impacts of biomass burning aerosols in northern Thailand, an accurate numerical biomass burning aerosol transport simulation system is required. Such system can provide details about the amounts and coverages of biomass burning aerosols as a function of time. Such information is useful for mitigating the impacts. Although it is a very important problem with big public impacts in northern Thailand, previous studies concerning biomass burning aerosol transport simulations in northern Thailand do not exist. A new-generation mesoscale numerical weather prediction (NWP) system, the Weather Research and Forecasting (WRF) model, is designed for both applications of atmospheric research and operational forecasting. The WRF model as it is coupled with Chemistry (WRF/Chem) has been used to evaluate aerosol processes because its online model permits the simulation of aerosol quantities easier compared to in-situ measurement and satellite data collected at different temporal and spatial resolutions.

A numerical biomass burning aerosol transport simulation model is necessary to provide an accurate simulations and forecasts of aerosol transport and the affected areas. Therefore, WRF/Chem has been used in this study to simulate a numerical biomass burning aerosol transport over northern Thailand since there is a lack of modeling studies have been documented on the air quality over this region, particularly the impact from biomass burning. However, Surussavadee and Aonchart (2013) has successfully employed the WRF model to provide high-resolution weather

forecasts in good agreement with satellite observations for Thailand and nearby regions. In this study, the performance compared to ground-based measurements from PCD despite overestimation or underestimation due to high uncertainties of biomass burning emission which occurring in specific regions. The WRF/Chem (Grell, 2005; Fast, 2006) is employed in this study. The biomass burning emissions data were from the Brazilian Biomass Burning Emissions Model (3BEM) (Freitas, 2011) are used. Simulated daily averaged PM10s covering a period of 3 months in year 2014 and 2015 were evaluated using measurements from 13 ground stations distributed in northern Thailand.

1.2 Northern Thailand air quality situation

Aerosol is an important issue of atmospheric chemistry which both directly and indirectly affect everyday life. This can cause problems in human health, atmospheric chemistry and the global regional climate (Pagowski and Grell, 2012; Benedetti and Fisher, 2007). The largest proportion of biomass burning is taking place in the tropics, where fires are referring to agricultural activities and deforestation (NASA). It has been a regular practice for land conversion and land clearing in many countries in SEA (Boonjawat, *et al.,* 2012) including northern Thailand. In the open biomass burning season, fires in northern Thailand and neighboring countries such as Laos and Myanmar were caused by most farmers trying to clean and fertilize land prior to planting (Wiwanitkit, 2008). The pollution layers covered many provinces in northern Thailand, including the provinces of Chiang Rai, Mae Hong Son, Chiang Mai, Lamphun, Lampang, Nan, Phrae and Phayao (Wiwanitkit, 2008; S. Sooktawee, 2015). The concentrations of ambient PM10 in these provinces have been automatically measured at the Air Quality Monitoring (AQM) station belonged to the PCD of Thailand (Chantara, 2012). In the dry season, the level of PM10 measured at provincial stations exceeds the standard level set by the PCD (120 $\mu g/m^3$) starting on the early of February, with the highest PM10 levels being reached in March each year (Sirimongkonlertkul1, *et al*., 2013).

Between February and April each year, droughts and rising temperatures along with the burning of agriculture, forest fires, and other pollution sources cover

northern Thailand in layers of smoke and haze. In the early of March 2007, Wiwanitkit (2008) reported a thick layer of pollution covered many provinces in northern Thailand caused a big environmental crisis in this area of Thailand. During 6 March 2007–17 March 2007, PM10 level in Chiang Mai is 204.25 $\mu g/m^3$ in average. In this time, incidence of respiratory illness in Chiang Mai reach 23 cases in average.

1.3 Objective

To develop and evaluate a numerical aerosol biomass burning transport simulation system for northern Thailand region.

1.4 Scope

This research simulated a numerical of biomass burning aerosol transport in northern Thailand using the WRF/Chem. The global gridded analyses from the NCEP FNL (Final), the global emission data from the REanalysis of the TROpospheric chemical composition over the past 40 years (RETRO) and the Emission Database for Global Atmospheric Research (EDGAR) and the daily biomass burning emission data from 3BEM were used in this study. The simulated daily averaged particulate matters with diameters less than 10 micron (PM10) at 5-km resolution covering the 3-month period of February–April of the year 2014 and 2015 were compared with those measured from 13 ground stations collected by PCD located in the northern Thailand.

1.5 Expected outcome

Understanding air quality can help us to manage the balance of air quality composition and concentration. Air pollutions models have come to play an important role on reliable estimation of pollutant concentrations. One of atmospheric simulation model recently used worldwide is the online WRF/Chem model. The model was used to simulate a numerical aerosol transport over northern Thailand. This study

is expected to help others, especially the author to better understand the problem of air quality. A numerical aerosol transport simulation system, on the other hand, is essential to help government to implement more effective urban air pollution reduction plans when fire fumes significantly affect air pollution levels in populated areas. Better understanding of smoke emissions and dispersions of biomass burning and their effects, however, is very important because it tells the area that will be affected by the smoke. Hence, emergency preparedness officials are responsible for managing these impacts.

CHAPTER 2
LITERATURE REVIEW

2.1 Biomass burning and forest fire

Biomass burning is recognized as one of the main dynamic of the earth system which affecting the global carbon cycle (Lin, *et al*., 2013; Paugam, 2015). Commonly, Biomass burning relates to the burning of grasslands, burnt of forest and agricultural activities such as clearing lands after harvesting (Calvo, 2010). These processes release smoke containing large amounts of atmospheric particulate matter or aerosols and trace gases into the atmosphere (Paugam, 2015; Calvo, 2010). Scientists estimate about 90% of biomass burning associated with human activities and only a small percentage of natural fires contributing to the total amount of biomass burned (Koppmann, 2005; NASA). Biomass burning releases large amount of trace gas emissions and aerosols to the atmosphere which significantly affecting the total global emissions. The estimated total global vegetation burned is around 8700 Teragram Tg per year which represents 3500 Tg of carbon in the form of carbon dioxide (CO2). The sources of fire including from savanna roughly 42%, agricultural wastes 23%, forests 17% and another from wood fuels 18% (Koppmann, 2005; Orueta, 2005). The more intense fires will produce the greatest amounts of aerosols. The aerosols play as sources of pollution that tends to be transported far distance and have the potential to affect global atmospheric chemistry. It transported by the intense heat and convective energy produced by the burning vegetation (Paugam, 2015).

The forest fires, on the other hand, are caused by naturally or from human caused. An example of a natural factor is lightning which sets trees on fire. While the man- made causes, for example, is throwing cigarette butts indiscriminately, clearing the forest to plant crops and forgot to turn off the bonfire (Nuryanto, 2015). Biomass burning plumes containing of aerosols, CO, and ozone which can be transported for hundreds or even thousands of miles in the tropics, shows that pollutants produced in one country can affect air quality in neighboring countries (WHO, 2006).

Although much of this transport occurs just above the mixed layer, redistribution of pollution which interacting with convection often leads to pollution layers in the upper troposphere (Kochanski, *et al*., 2012). In 2006, the World Health Organization (WHO) published air pollutions guidelines, but the local air quality that is affected by biomass burning emissions is still incomprehensible or cannot be measured properly. (Aouizerats, 2015).

In SEA, biomass burning usually occurs during February through April and peaking in March. Figure 2.1 is the distribution of active biomass burning at SEA during 1996-2009 in the monthly average according to the Along Track Scanning Radiometer (ATSR). From December to March, burning covered most of Indochina caused by the gradual deployment of biomass burning areas from the north and south of the central peninsula. (Vietnam, Cambodia and Laos). the area of the fire began to shrink since April and drastically reduced in May, this occurs when the rainy season in the southwest begins to rain as shown in Figure 2.2 (Yen, *et al*., 2013).

2.2 Aerosol

2.2.1 Aerosol in the atmosphere

Aerosols can be found in the atmosphere, particularly in air that is nearest to the ground (Skinner and Murck, 1928) include over oceans, deserts, mountains, forests, ice, and every ecosystem in between. An aerosol is generally defined as a suspension of particulate matter (PM, extremely tiny, solid particles or liquid droplets) in gas (Skinner Murck, 1928; William, 1999; Zhu, *et al*., 2012). Liquid aerosols (e.g. fog and clouds) and solid aerosol particles - sometimes called particulates (e.g. volcanic ash, smoke from forest fires, blown sea salt, blown dust and loess, and pollen) (Skinner and Murck, 1928) are present throughout the atmosphere with size ranges from a few nanometers to tens of micrometers (Myhre, *et al*., 2013) and largely causes hazy skies. In the atmosphere, they are usually stable for at least less than a second and in some cases may up to several years (William, 1999).

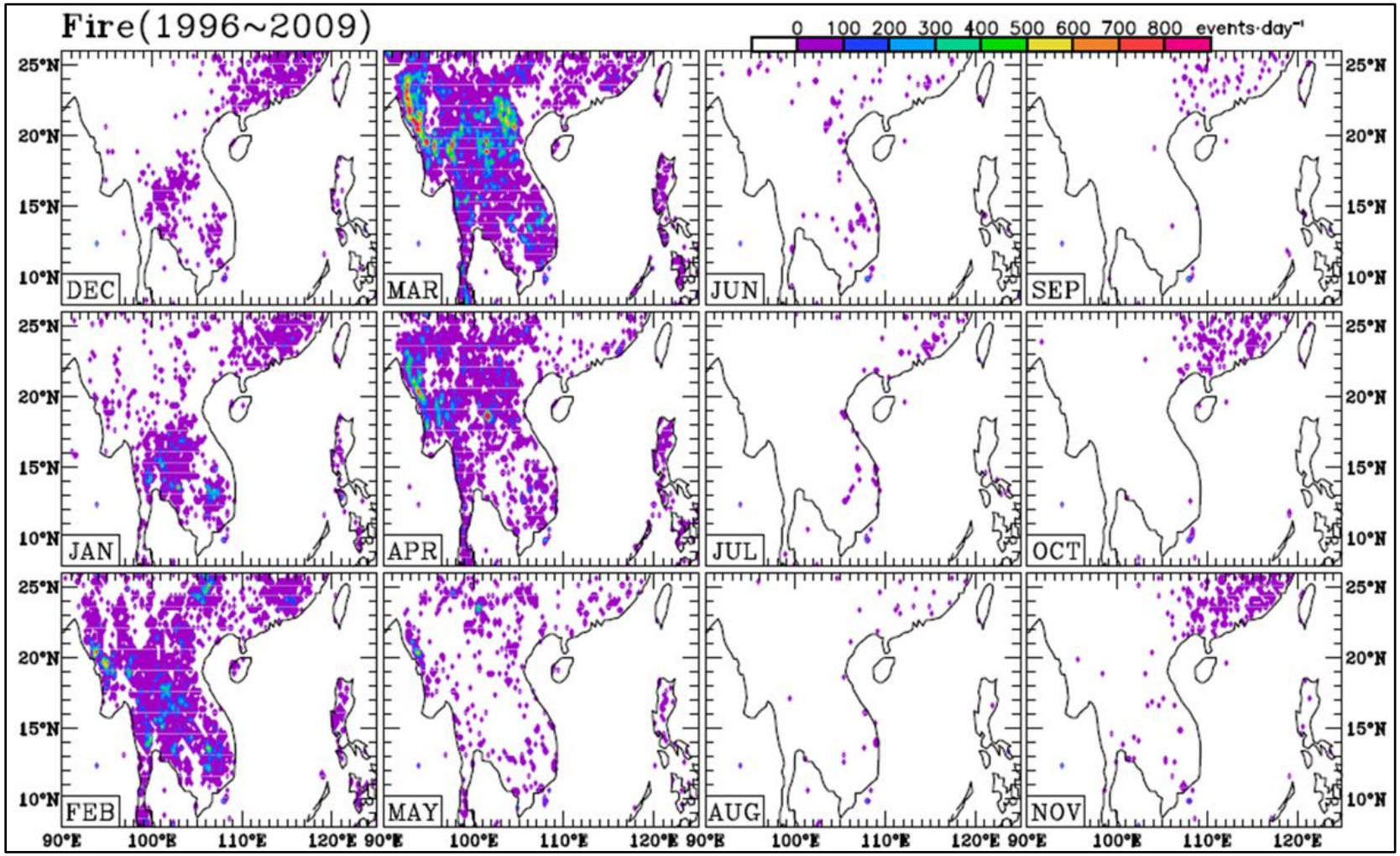

Figure 2.1 The monthly mean of fire distributions between 1996 - 2009 observed by ATSR (Yen, *et al.*, 2013).

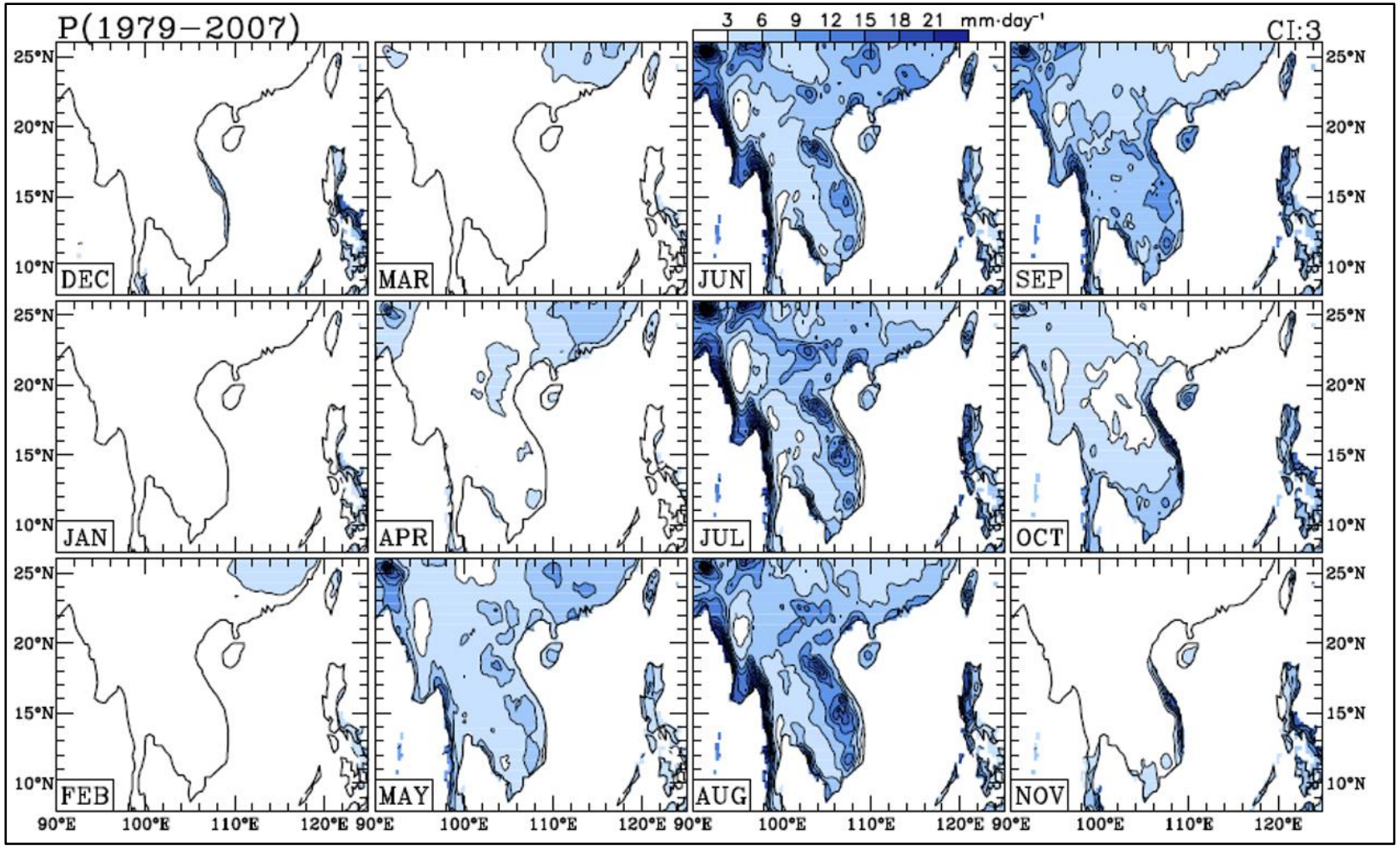

Figure 2.2 The monthly average rainfall of the Indochina Peninsula between 1996 – 2009, a precipitation product generated from the rain-gauge at 0.25 daily grid (Yen, *et al.*, 2013).

2.2.2 Classification of aerosols

The physical and chemical compositions of aerosols related to their meteorological conditions and emission sources (Zhu, *et al.*, 2012). Variation in height of aerosol source (e.g. sand hill tops, steppe, and plant chimneys) and different reliefs of the surface cause different dependencies of the aerosol composition in the atmosphere on meteorological condition (Kondratyev, *et al.,* 2006). Regarding to their sources, aerosols enter the atmosphere from both natural and anthropogenic sources (Skinner and Murck, 1928) as shown in Figure 2.3. Anthropogenic sources as human activities include transportation, industrial activities, fires, mechanical sources, and human induced changes in vegetation. While natural phenomena such as dust storms, sea spray, forest fires, volcanoes and vegetation produce aerosols as well (Zhu, *et al.*, 2012). These both anthropogenic and natural sources release primary and secondary aerosol.

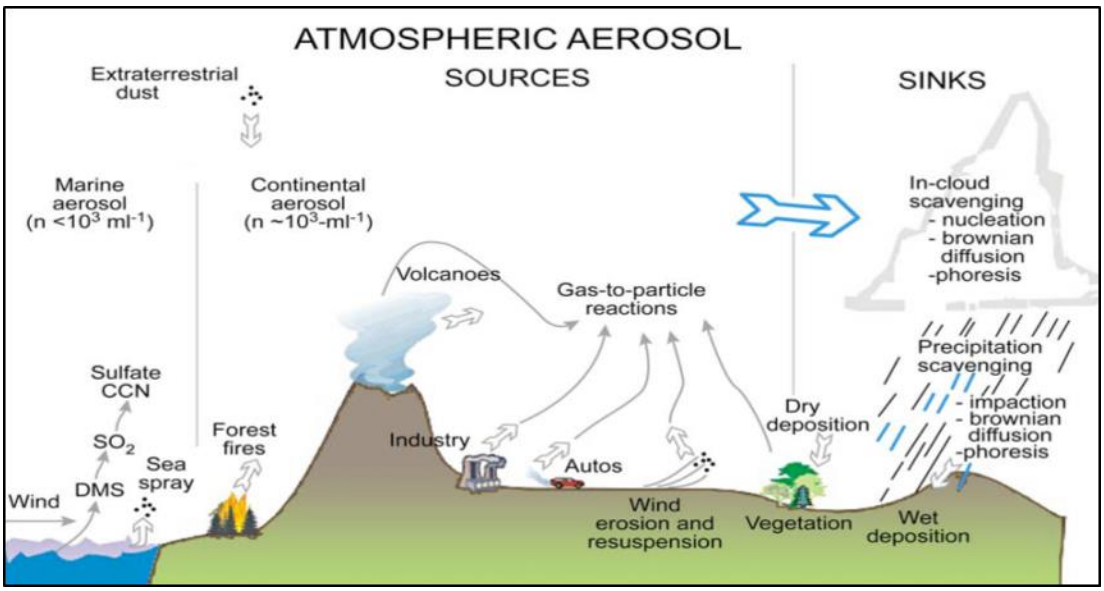

Figure 2.3 Atmospheric aerosol sources (Zhu, *et al.,* 2012).

2.2.3 Aerosol impacts

Atmospheric aerosols and particulate matter (PM), which are often used synonymously, are one of the most challenging problems both for air quality and for global regional climate. They have largely been kept separate in both the scientific and policy communities (Zhu, *et al.,* 2012). Studies represent that air pollution in the city is

associated with increased daily mortality, hospital admissions such as for cardiovascular and respiratory diseases, and physiological changes in the body. Particulate problems can cause long-term effects on public health and reduce life expectancy, especially in vulnerable people such as young people, the elderly and people with pre-existing heart and lung disease (TGN, 2012). Based on known health impacts, short-term (24-hour) and long-term (year-on-year) guidelines are required for both PM pollution indicators (PM10 and PM2.5). World Health Organization (WHO, 2006) issued an *Air Quality Guidelines* to inform policy-makers from around the world on the right targets for policies related to air quality management. The particulate boundary value for human health protection from WHO is shown in Table 2.1 (WHO, 2006). Aerosols may impact the climate through both directly (the particle itself absorbs or spreads radiation) and indirectly (particles that act as cloud condensation nuclei) effects (Zhu, *et al.,* 2012).

Table 2.1 The value of particulate boundaries for human health protection from WHO. (WHO, 2006)

Pollutant	Limit value	Averaging period
PM10	50 µg/m^3	24 hours' mean
	20 µg/m	Annual mean
PM2.5	25 µg/m^3	24 hours' mean
	10 µg/m	Annual mean

2.3 WRF/Chem

2.3.1 The introduction of WRF/Chem

The Weather Research and Forecasting (WRF) model as it is coupled with Chemistry **(**WRF/Chem) is an online- coupled meteorology- air quality model (Grell, *et al*., 2005; Fast, *et al*., 2006; Zhang, *et al*., 2010) which predicts chemical and

meteorological components simultaneously (Gupta and Mohan, 2013). To get more information about the WRF model, readers are directed to the WRF User Guide (http://www2.mmm.ucar.edu/wrf/users/docs/user_guide_V3/contents.html). With nested grid capabilities, WRF/Chem simulation model can be easier than in-situ and remote sensing data collected at different temporal and spatial resolutions (Wang, *et al*., 2013).

2.3.2 The modeling system of WRF/Chem

Based on the WRF/Chem User's Guide, there are four main programs in the WRF/Chem modeling system which follows the structure of the WRF model (Figure 2.4):

1) The WRF Preprocessing System (WPS)
2) WRF-Var
3) WRF solver (ARW)
4) Post-processing and visualization tools.

In addition, WRF/Chem needs to provide additional gridded input data associated with emissions provided by WPS (area of dust erosion) or read during initialization of real.exe (eg biogenic emissions, GOCART background fields, biomass burning, etc.), or read during WRF fraud execution (eg, anthropogenic emissions, boundary conditions, volcanic emissions, etc.).

2.4 WRF/Chem-emissions data

Because of variation data sources used in the WRF/Chem simulation, it must prepare externally an additional set of data representing the source of the chemical parameters. PREP-CHEM-SRC (Freitas, *et al.*, 2011) developed at CPTEC, Brazil, is a pre-processor that very useful to generate the anthropogenic/ biogenic/ biomass/ volcanoes emissions in the WRF/Chem grid for regional and global models. There are three options of emissions (biomass burning, anthropogenic, biogenic, etc.) that can be chosen by the user according to the modeling system used. users may use all options or select only a portion of the overall set available (Steven, *et al.*, 2012; Freitas, *et al.*, 2011). In this study for biogenic and volcanoes emissions are default in WRF/Chem.

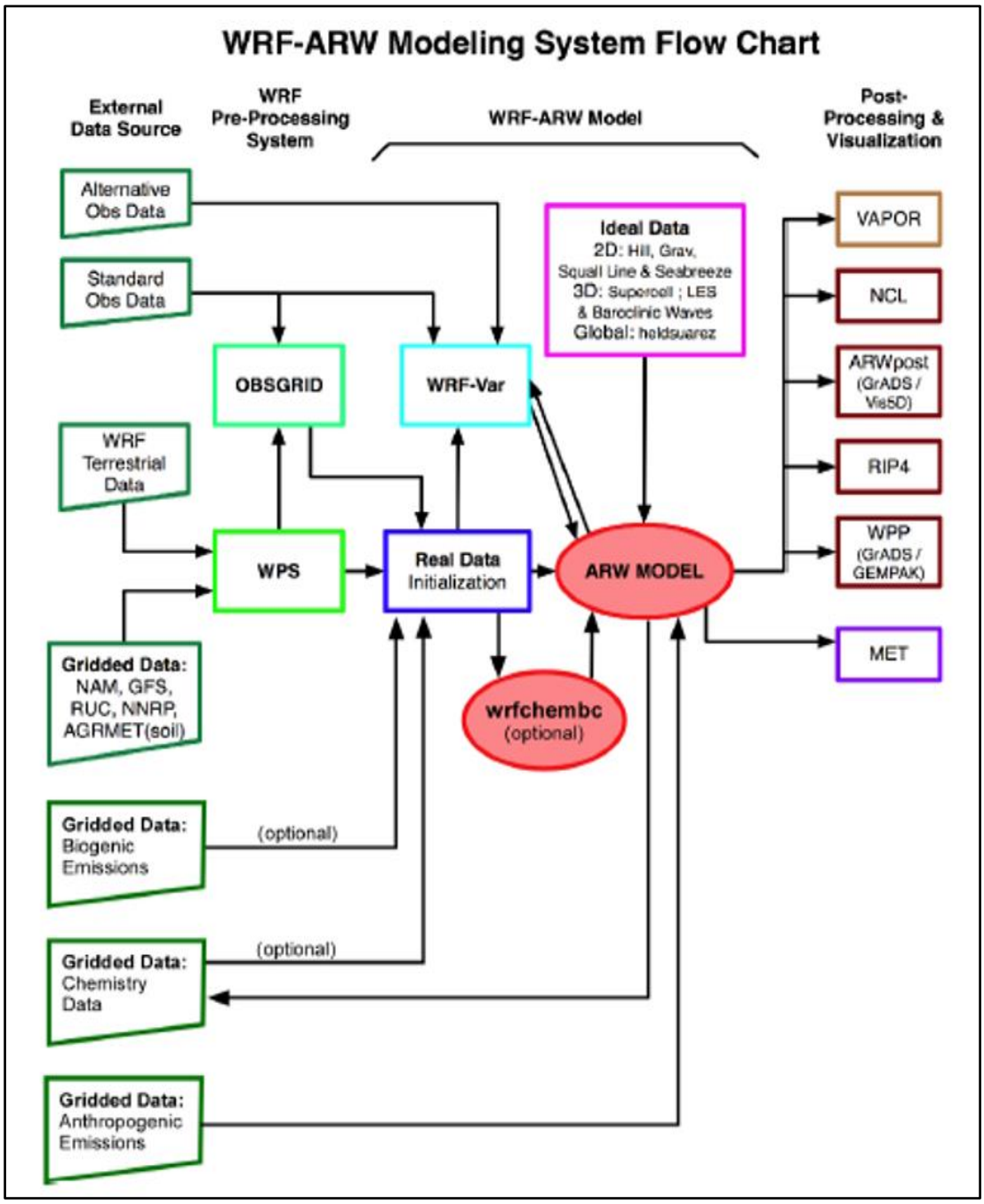

Figure 2.4 WRF-ARW modeling system flow chart (Steven, *et al.*, 2012).

2.4.1 Urban/industrial emissions

There are three options for available anthropogenic emissions with different time horizons, resolutions and different ranges of species; Reanalysis of the TROpospheric chemical composition over the past 40 years (RETRO), based on the

year 2000, provides global coverage emissions data at 5-degree spatial resolution monthly model database. The unit of each emission is kg (species) m^{-2} dy^{-1}. The parameters that available in the RETRO shown in Table 2.2. Emission Database for Global Atmospheric Research (EDGAR) provides emissions data at a 1-degree spatial resolution. It is an actual and current global greenhouse gases and air pollution anthropogenic emissions data based on the year 2000 that do not vary in time. The available species are N2O, CO_2, CO, CH_4, SO_2, SF_6, NO_x and NMVOC. The U.S. Environmental Protection Agency (EPA) National Emissions Inventory (NEI) 2005 inventory at standard 4-km resolution data set (for USA only) is an appropriate regional urban emission inventory (local and regional scale) for 48 contiguous states in the United States, Southern Canada and northern Mexico.

For primary anthropogenic aerosol emissions of organic carbon (OC), black carbon (BC), Sulfur dioxide (SO2) and dimethylsulfide (DMS) are provided by Goddard Chemistry Aerosol Radiation and Transport (GOCART) which is at 1-degree spatial resolution on a monthly basis model databases (Freitas, *et al.*, 2011).

Table 2.2 List of available parameters in the RETRO program. (Freitas, *et al.*, 2011)

Acids	C_4H_{10}	Ethene	Other Aromatics
Alcohols	C_5H_{12}	Ethers	Other VOC
Benzene	C_6H_{14} plus higher alkanes	Ethyne	Toluene
C_2H_2	Chlorinated Hydrocarbons	Ketones	Trimethylbenzene
C_2H_4	CO	Methanal	Xylene
C_2H_6	Esters	NO_x	
C_3H_8	Ethane	Other Alkanals	

2.4.2 Smoke plume rise model and biomass burning emissions

There are two techniques to provide Emissions from biomass burning or wildfire. The Brazilian Biomass Burning Emission Model (3BEM) and the Global Fire Emissions Database (GFED). The 3BEM database is a combination of three fire product databases include the Wildfire Automated Biomass Burning Algorithm (WF ABBA) Geostationary Operational Environmental Satellite (GOES) processed half-hourly fire hot spot analyses for the Western Hemisphere, The Brazilian National Institute for

Space Research (INPE) fire product based on the Advanced Very High-Resolution Radiometer (AVHRR) aboard the NOAA satellites, and The Moderate Resolution Imaging Spectroradiometer (MODIS). The GFEDv2 is an 8-day or 1-month temporal resolution inventory at a 1-degree spatial resolution. The emissions of this database are interpolated to the model grid. The available parameters is the same as a list as shown in the Table 2.3 (Freitas, *et al.*, 2011). GFEDv4 is the current version of this database with 0.25-degree spatial resolution and available from 1997 until the most recent year of 2015.

Table 2.3 List of parameters for within the PREP-CHEM-SRC (Freitas, *et al.*, 2011)

CO	i_butane	n_hexane	Butanols
CO_2	n_butane	isohexanes	cyclopentanol
CH_4	2_pentene	heptane	phenol
NHMC	1_pentene	octenes	Formaldehyde
C_2H_2	n_pentane	terpenes	Acetald
C_2H_4	2_Me_Butene	benzene	Hydroxyacetaldehyde
C_2H_6	2_Me_butane	toluene	Acrolein
C_3H_4	pentadienes	xylenes	Propanal
C_3H_6	Isoprene	ethylbenzene	Butanals
C_3H_8	cyclopentene	styrene	Hexanals
1_butene	cyclopentadiene	polycyclic aromatichydrocarbons (PAH)	Heptanals
i_butene	2_me_1_pentene	Methanol	Acetone
cis_2_butene	4_me_1_pentene	Ethanol	2_Butanone
tr_2_butene	1_hexene	2_Propanol	2_3_Butanedione
butadiene	hexadienes	1_propanol	Pentanones
Hexanones	Acrylonitrile	NH_3	Heptanones
Heptanones	Propionitrile	HCN	Octanones

Table 2.3 List of parameters for within the PREP-CHEM-SRC (Freitas, *et al*., 2011) (cont.)

Octanones	pyrrole	cyanogen	Benzaldehyde
Benzaldehyde	trimethylpyrazole	SO_2	Furan
Furan	methylamine	DMS	H_2
3_Me_Furan	dimethylamine	COS NOx	NO_x
2_Me_Furan	ethylamine	CH_3Cl	NO_y
2_ethylfuran	trimethylamine	CH_3Br	N_2O
2_5_dime furan	n_pentylamine	CH_3I	benzofuran
2_4_dime furan	2_me_1_butylamine	Hg	Propanoic
Tetrahydrofuran	particulate matter less than 2.5 µm in diameter (PM2.5)	total carbon (TC)	organic carbon (OC)
2_3_dihydrofuran	black carbon (BC)	total particulate matter (TPM)	

The fire-emissions data in the WRF/Chem model is provided by wrffirechemi_d01. This data file calculates the rise of fire fumes based on the ambient temperature and wind parameter. The emission to the forecast is then given as a vertical distribution based on the calculation of the increase in plume (Steven, *et al.*, 2012). Table 2.3 shows the PREP-CHEM-SRC's available species. The unit of each emissions is kg (species) m^{-2} dy^{-1} (Freitas *et al.*, 2011).

2.5 Previous studies

Previous studies about models and applications of WRF/Chem to the distribution of pollution from biomass burning and forest fires have been carried out using the previous version. Wang, *et al*. (2013) used WRF/Chem version 3.1 to learn about the transport of smoke in the SEA's Maritime Continent (MC), including the islands of Malaysia and Indonesia. This study deals with smoke events between

September to October 2006. WRF/Chem smoke emissions were determined according to the Fire Locating and Modeling of Burning Emissions (FLAMBE) database derived from MODIS. This study aims to combine the model simulations, ground measurement and satellite observations to study transport of smoke routes through MC at a higher resolution than previous research. This study found correlations between the simulated PM2.5 dry mass and the observed PM10 at 49 stations in Singapore and Malaysia are good for most stations which is greater than 0.7.

Guptanand Mohan (2013) studied the effects of long–range transport of atmospheric pollutants over megacity Delhi during June 2010 using WRF/Chem version 3.2. Anthropogenic emissions obtained from EDGAR database were processed by PREP-CHEM-SRC program. Megacity Delhi experiences subtropical climatic conditions. High PM10 concentrations are associated with the long-distance transport processes that typically occur in the summer. This study shows that the WRF/Chem model performs well for sub-tropical urban air sightings although there is scope for improvements for predictions that are inconsistent with smoother emission inventories.

Lin, *et al.*, in 2014 studied about the air mass transport related to the biomass burning in Indochina using WRF/Chem version 3.2.1. Biomass combustion emissions obtained from FINNv1 inventory are used in the WRF/Chem model. This research analyzed the CO, O3 and PM10 concentrations which are associated with biomass burning emissions from SEA during February to April of the year 2006 until 2009. WRF/Chem simulations captured enough the concentration of PM10 and O3 but underestimated the CO concentration at the observation during March 17-18. The underestimation of CO concentration is very likely due to early atmospheric condition.

Nuryanto (2015) used WRF/Chem to simulate the event of forest fires on March 7, 2014 on the island of Sumatra, Indonesia. The biomass burning data is obtained from Fire Inventory from NCAR (FINN). The 0.5-degree gridded Global Forecast System (GFS) at every 6 hours was used as the initial and boundary conditions in the model. This study focused only on CO compounds as one of the forest fire's emissions. The model has been evaluated against satellite image of MODIS Aqua platform. This study found that the amount of CO in the plume is too low using the simulation model. It may due to underestimation of CO in the emission inventory. To

get a better result, it is recommended that the ratio of CO in fire emissions should be reassessed.

Aouizerats, *et al.*, (2015) used WRF/Chem version 3.4 to study the emissions and evolution of aerosol particles from biomass burning in Sumatra. Simulations for this study include Sumatra island, Singapore and south of peninsular Malaysia. This simulation covered a 4-month period (1 July to 31 October 2006) including a big event of fire episode in Sumatra that occurred in October. The simulation included biomass burning emissions from GFED3, anthropogenic from the EDGARv4 and RETRO and biogenic from MEGANv2.1 prepared by the PREP-CHEM-SRC. This study compared the output from simulations with the observations ground-based measurements monitored by Singapore's National Environment Agency (PM10 and CO) and AOD that measured by Ozone Monitoring Instrument (OMI), Multi-angle Imaging Spectroradiometer (MISR), Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and MODIS. The comparison with PM10 and CO observations performed that the WRF/Chem model successfully reproduces the surface concentrations well. However, the AOD is underestimated which may cause by tropical cirrus cloud that affects AOD measurements or a regional transport particles layer misinterpreted in the simulation.

Zhong, *et al*., (2015) studied about air quality in East and South Asia in 2007 at 20 km x 20 km spatial resolution using WRF/Chem version 3.5. This study simulated WRF/Chem simulation using two different anthropogenic emission inventories (EDGAR and the Regional Emission Inventory in Asia (REASv2)) and evaluated the model performance for PM10 concentrations, as well as O3, SO2, and NO2 mixing ratios, using ground measurements. The simulation included biogenic emissions from the Precursors of Ozone and their Effect on the Troposphere (POETv1) and biomass burning emissions from GFEDv3 inventory. Sea salt and dust emissions are calculated online using the sea salt schemes and the dust transport model, respectively. The study found a large difference between both anthropogenic inventories: The Regional Emission Inventory up to 160% for primary PM10, 190% for NO and 500% for CO emissions. For future emission models in East and South Asia, better development and evaluation is needed for particulate and gaseous pollutants.

CHAPTER 3
METHODOLOGY

3.1 Study area

Thailand is located at the center of the Indochinese peninsula in SEA. It is bordered by the Andaman Sea, the Gulf of Thailand, the Indian Ocean and the countries of Burma (Myanmar), Laos, Cambodia and Malaysia. The study area covers the region of the north region of Thailand. Northern Thailand is largely mountainous representing the most heavily forested areas of the country. The soil is fertile and farming is widespread. The climate is typical of tropical mountains with clearly delineated wet and dry seasons.

Smoke and haze situation directly affects the air quality in all provinces in the northern Thailand (Chiang Rai, Mae Hong Son, Chiang Mai, Lamphun, Lampang, Nan, Phrae and Phayao), starting at the beginning of March and decreasing in early April (Sooktawee, S., 2015). In these provinces, during severe haze, the level of PM10 measured at provincial stations exceeds 120 $\mu g/m^3$ which is the standard level set by the PCD from February, with the highest PM10 levels being reached in March each year. Commonly, northern Thailand faces smoke and haze problems which are caused by wild fires and open-space burning, and has resulted in environmental problems which become an emerging new "disaster" issue over the last decades (Sirimongkonlertkul1, *et al*., 2013). The geographic location of northern Thailand is north latitude 20 degrees north (27 minutes north), South at latitude 17 degrees north (10 minutes north), East longitude 101 degrees (10 minutes east on), West of longitude 97 degrees (22 minutes east) with a total population of 6,133,989 as of 2011.

3.2 Research procedure

The procedures in this study were divided into 6 stages, i.e. observation data collection phase consisting of Ground measurement data, time periods selection

for simulation, domain determination to use in simulation, generating emissions data that will be used in WRF/Chem, WRF/Chem simulation, and compare simulated PM10 with ground measurements. The series of research procedures can be depicted in a flowchart of the study as outlined in Figure 3.1.

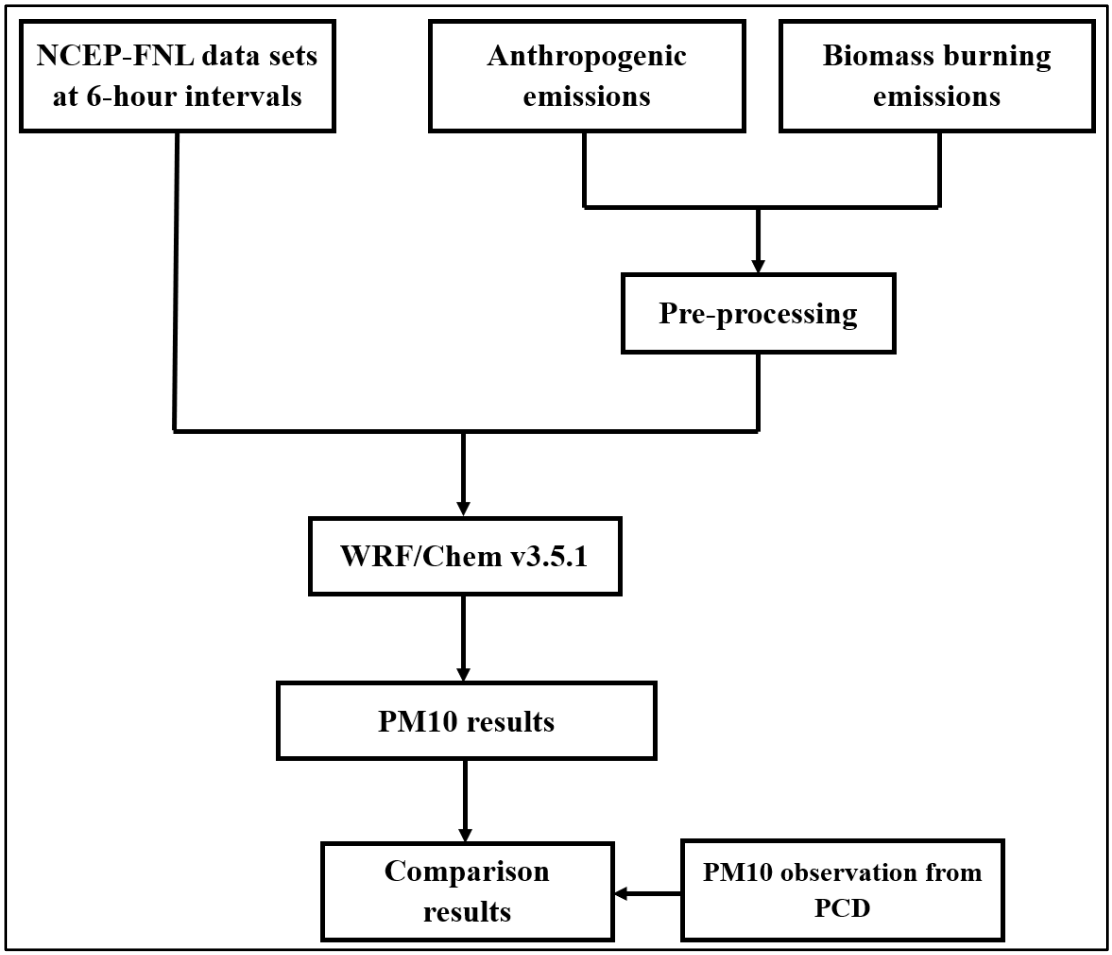

Figure 3.1 Flowchart of the study

3.2.1 Ground measurement data

Hourly PM10 data used for this study were obtained from 13 measurement stations belonging to the PCD of northern Thailand. Overview of the stations used in this work and their geographical location in longitude and latitude shown in Table 3.1 and in Figure 3.2.

Table 3.1 Monitoring stations in northern Thailand

Station ID	**Latitude**	**Longitude**	**Province**
57T	19.9092	99.8234	Wiang, Mueang, Chiang Rai
73T	20.4272	99.8837	Wiang Pang Kum, Mae Sai, Chiang Rai
35T	18.8406	98.9697	Chang Phueak, Mueang, Chiang Mai
36T	18.7911	98.9900	Si Phum, Mueang, Chiang Mai
67T	18.7889	100.7764	Nai Wiang, Mueang, Nan
70T	19.1639	99.9027	Wiang, Mueang, Phayao
69T	18.1289	100.1623	Na Chak, Mueang, Phrae
58T	19.3047	97.9710	Chong Kham, Mueang, Mae Hong Son
37T	18.2783	99.5064	Phra Bat, Mueang, Lampang
38T	18.2507	99.7640	Sop Pat, Mae Mo, Lampang
39T	18.4197	99.7273	Ban Dong, Mae Mo, Lampang
40T	18.2827	99.6599	Mae Mo, Mae Mo, Lampang
68T	18.5674	99.0080	Nai Mueang, Mueang, Lamphun

3.2.2 Select time periods for simulation

In northern Thailand, particulate matter mostly released from high activities of open burning and forest fires which usually take place during the dry season from December to early April of the following year (Amnuaylojaroen, *et al*., 2011). In this study, the simulated of hourly and daily averaged PM10 covering the 3-month period of February – April of the year 2014 and 2015, due to the highest particulate matter levels being reached in this month each year.

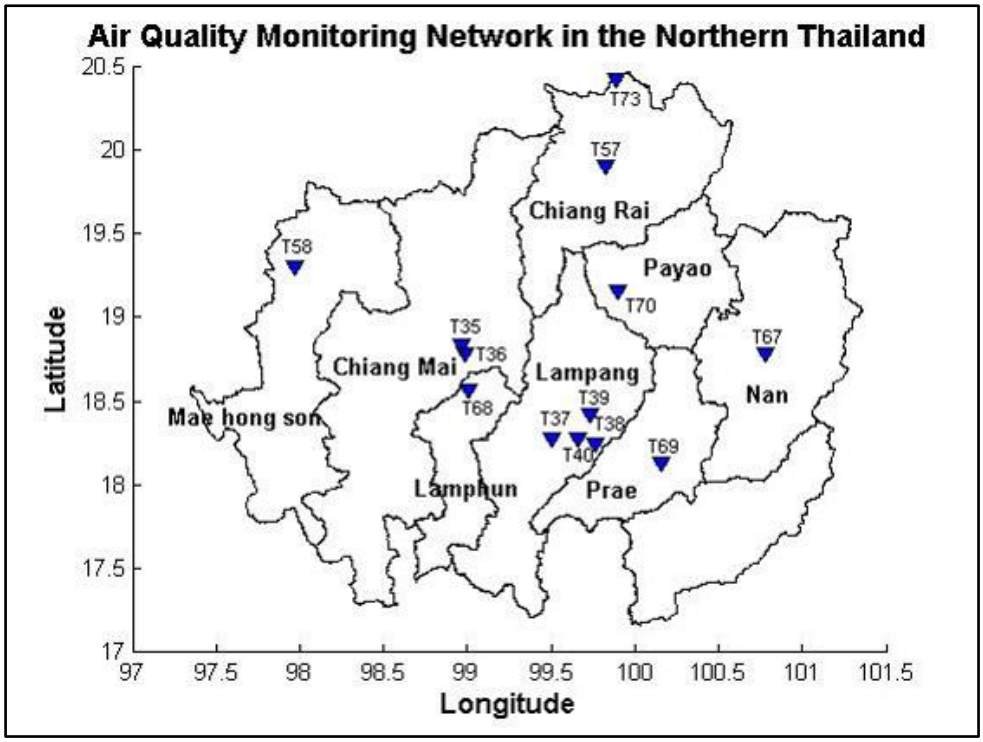

Figure 3.2 Air monitoring network locations of 13 ground stations in northern Thailand employed in this study.

3.2.3 Emissions data

The emissions are obtained from the PREP-CHEM-SRC version 1.5. It reads global emissions from the RETRO / EDGAR anthropogenic database and the static GOCART background field and gives them the convert_emission program (included in the WRF/Chem package) to generate a rolled-up netCDF emission file to run WRF/Chem. To interpolate the emission fields to the model grids, Mercator projection will be used. The daily biomass burning emission data gathered from 3BEM.

3.2.4 WRF/Chem simulation

3.2.4.1 Model input and simulation details

The WRF/Chem version 3.5.1 has been selected for this study. WRF physics options employed in this study follow those successfully used in Surussavadee and Aonchart (2013). The WRF/Chem model is configured to cover north part of Thailand with 120x120 grid points centered at latitude 18.97°, longitude 99.4°, a 5 km grid resolution and 41 vertical levels to 50 hPa. The model configuration included two

successive nested domains, with grid-spacing of 15 km (the parent domain, domain 1) and 5 km (domain 2) as shown in Figure 3.3. The grid points of the inner most domain (domain 2) which is focused over northern Thailand were used in the evaluation procedure.

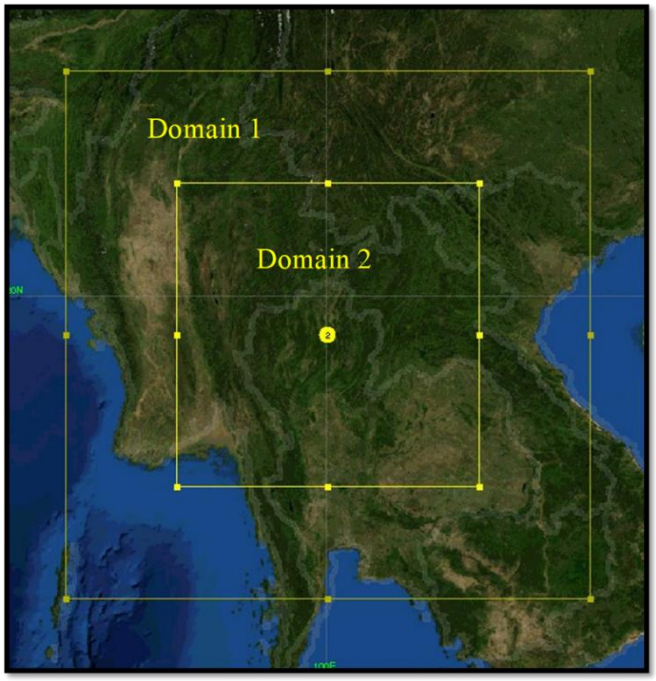

Figure 3.3 Geographical position of the model grid domains (D1: 15 km x 15 km, D2: 5 km x 5 km).

Boundary and initial conditions are assimilated from NCAR/NCEP Final Analysis (FNL), which are on a 1-degree x 1-degree grid prepared operationally every 6-hours.

3.2.4.2 Compare simulated PM10 with ground measurements

Numerical simulation results of PM10 by WRF/Chem model compared to the PM10 data from PCD. To compute PM10 at the ground stations, horizontally linear interpolation followed by vertically linear interpolation between neighboring levels were used.

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 Ground-based measurement of hourly average PM10 dry mass

In the northern Thailand, open biomass burning is an important sources of high particulate matter concentrations, mainly in the dry month between February and April. These months are in the cold season in Thailand when the air is dry and the biomass burning activities are very active. The biggest contributors to air pollution in northern Thailand were caused by human activities, including burning of agricultural fields and forested areas. Based on 1998-2002 data, the burning season was mainly related to the collection and harvest of forest products (37%), hunting (22%), and burning of agricultural crop residue (17%) (Tiyapairat and Sajor 2012). Each year between February and April, farmers throughout northern Thailand as well as the region's neighboring countries burn an incredible amount of vegetation with the hopes of better managing their agricultural waste and clearing up the ground for the next round of crops. This practice typically falls between these months and has sparked intense criticism and controversy.

The observed PM10 dry mass concentrations used for this work were obtained from 13 measurement stations belonging to the PCD of northern Thailand. The study area and locations of the 13 ground stations used in this study shown in Figure 3.2. 24-hour average concentrations of PM10 were plotted for the whole two years, 2014 and 2015 as shown in Figure 4.1. It shows that the concentrations are high in February and March of both years.

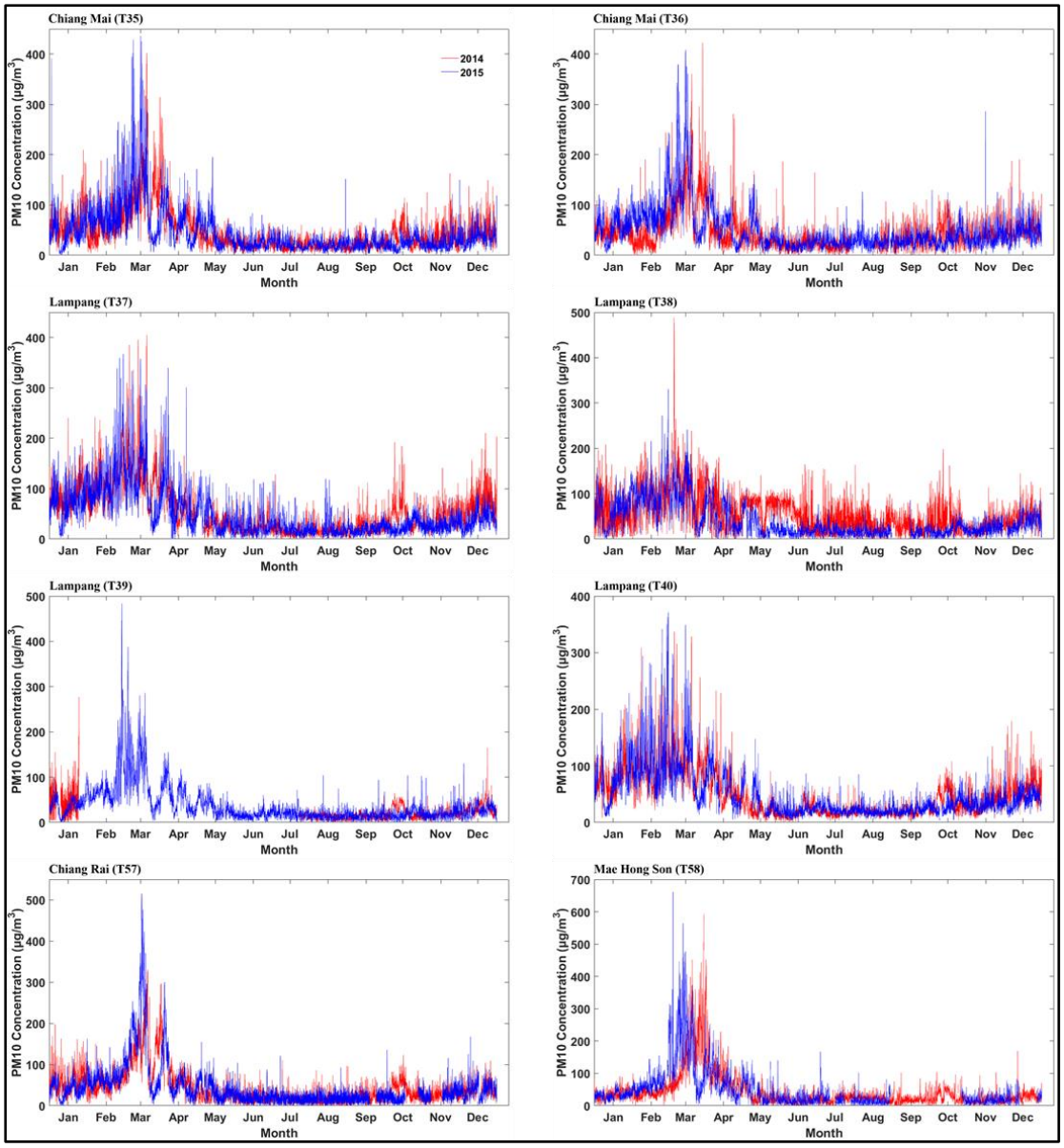

Figure 4.1 Hourly-averaged PM10 concentrations (µg/m^3) covering the whole year of 2014 and 2015 for 13 stations located in northern Thailand.

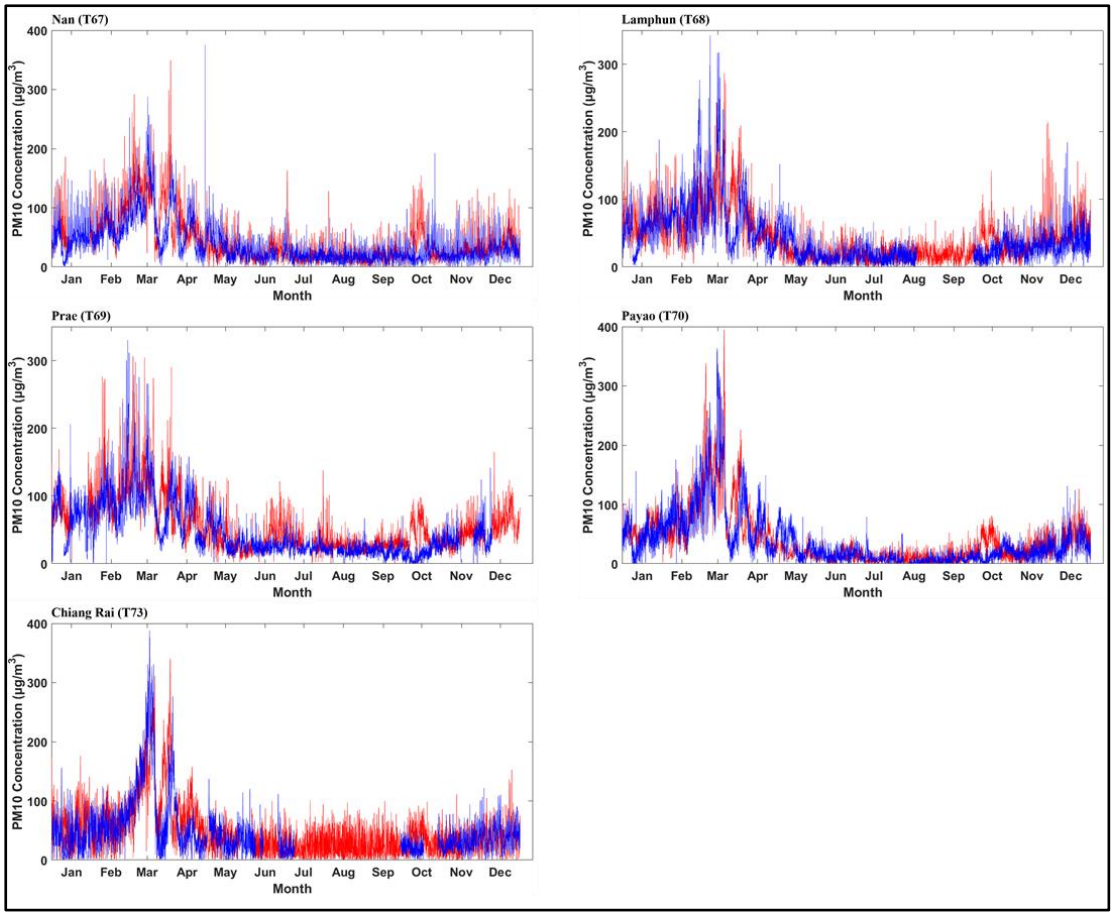

Figure 4.1 Hourly-averaged PM10 concentrations (µg/m^3) covering the whole year of 2014 and 2015 for 13 stations located in northern Thailand. (cont.)

4.2 Comparison of hourly average observed and simulated PM10 dry mass

Smoke and haze episodes due to open biomass burning season in northern Thailand have been simulated using WRF/Chem. The simulation included anthropogenic and biomass burning emissions. The global emission data from the REanalysis of the TROpospheric chemical composition over the past 40 years (RETRO) and the Emission Database for Global Atmospheric Research (EDGAR) anthropogenic inventories (Freitas, 2011), the primary anthropogenic aerosol emissions of black carbon (BC), organic carbon (OC), Sulfur dioxide (SO2) and dimethylsulfide (DMS) at $1^{\circ} \times 1^{\circ}$ resolution on a monthly basis provided by Goddard Chemistry Aerosol Radiation and Transport (GOCART) model databases and the daily biomass burning

emission data from 3BEM were used in this study. The 3BEM emission data were fed into the simulations daily.

Table 4.1 MEs (E[Simulations–Observations]), RMSEs, and CCs of Simulated Hourly Averaged PM10 Dry Mass concentrations (μg/m^3) for each Ground Station during February–April 2015.

Stations	**2015**		
	ME	**RMSE**	**CC**
T35	5.9704	78.7644	0.4137
T36	-5.0510	67.2484	0.5029
T37	2.4622	76.9301	0.4401
T38	2.9118	50.9065	0.5989
T39	1.0070	63.7230	0.6348
T40	-3.1633	63.0872	0.5019
T57	-2.6999	74.1863	0.6434
T58	2.4490	130.2015	0.5816
T67	2.5172	91.8654	0.4330
T68	2.8960	69.2604	0.4004
T69	-2.2011	53.7930	0.5307
T70	2.6832	59.5869	0.6891
T73	0.8272	92.9748	0.6420

The biomass burning aerosol transport for the study area was simulated continuously starting from January 30th and to April 30th of 2014 and 2015 to ensure that chemical variables in the model integrate through the period. Simulations for the first 2 days were treated as a spin-up period and were not used. WRF/Chem simulated PM10 at 5-km resolution were used in this study. To compute PM10 at the ground stations, horizontally linear interpolation followed by vertically linear interpolation between neighboring levels were used.

We evaluated the model performance using the mean error (ME), the root mean square errors (RMSE) and correlation coefficient (CC) between the hourly observed and hourly modeled PM10 dry mass concentrations. Table 4.1 shows mean errors (E[Simulations – Observations]; MEs), root mean square errors (RMSEs), and correlation coefficients (CCs) of simulated hourly averaged PM10 dry mass concentrations (μg/m^3) for each ground station during February–April, 2015. MEs for most stations except stations T35, T36, and T40, are less than 3 μg/m^3 for the year 2015. The station with maximum RMSE is T58. Correlations between simulations and observations are good for most stations, where CCs are ranged from 0.4 to 0.69.

Table 4.2 MEs (E[Simulations – Observations]) and RMSEs of Simulated Hourly Averaged PM10 Dry Mass Concentrations (μg/m3) for all 13 Ground Stations during February–April 2015 for Different Observed Concentration Ranges.

Range (μg/m^3)	**ME**	**RMSE**
0-100	3.06	54.61
100-200	2.76	**95.72**
200-300	-28.67	**168.71**
300-400	-72.78	**201.40**
>500	-148.00	**214.16**

Boldface: RMSEs below the minimum listed in column 1, indicating good utility.

Since values of hourly averaged PM10 dry mass concentrations cover a wide range, Table 4.2 shows MEs and RMSEs of simulated hourly averaged PM10 dry mass concentrations for all 13 ground stations during February–April of the year 2015 computed separately for different concentration ranges divided using observations. RMSEs shown in boldface are those below the minimum of the concentration range listed in the first column, which indicate good utility. Simulated PM10 dry mass concentrations are useful for all ranges and have good utility for concentrations above 100 μg/m^3. Simulations are slightly positively biased for concentrations below 200 μg/m^3 and are negatively biased otherwise.

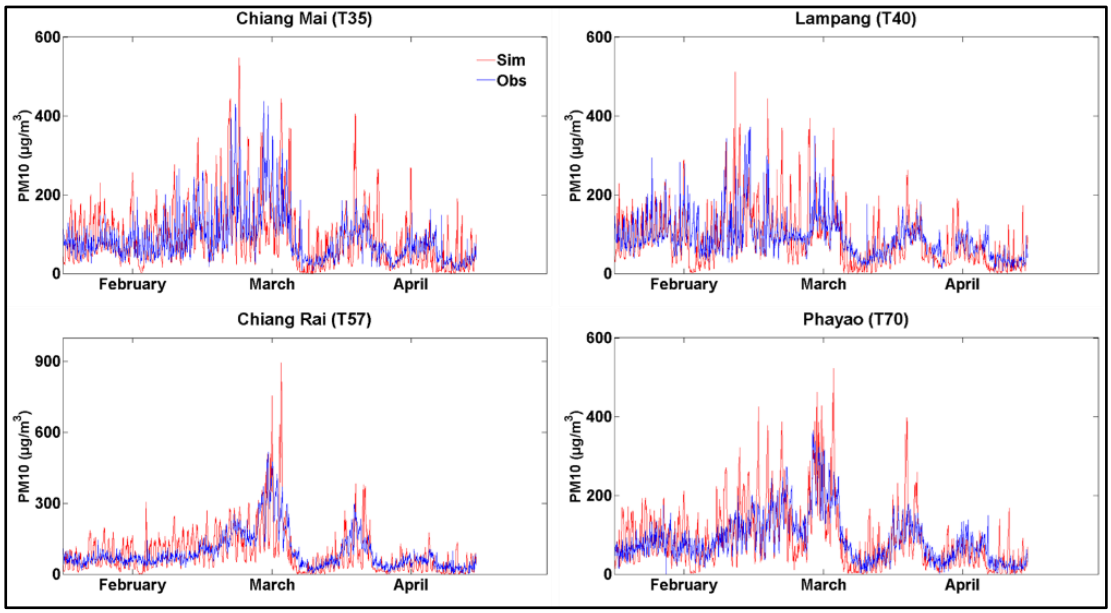

Figure 4.2 Comparisons of simulated (red) and observed (blue) hourly averaged PM10 dry mass concentrations (µg/m^3) for 4 ground stations during February–April 2015.

Figure 4.2 compares simulated and observed hourly averaged PM10 dry mass concentrations for the 4 ground stations for the full 3-month period of February–April for the year 2015. The figures show that simulated PM10 concentrations can predict lows and highs of observed PM10 concentrations quite well for all stations for the full 3 months.

Figure 4.3 shows scatterplots between simulated and observed hourly averaged PM10 dry mass concentrations for 13 ground stations for the full 3-month period of February-April 2015. Simulations agree well with observations. The overall correlation coefficient between simulations and observations is 0.55. The scatterplot is consistent with results shown in Table 4.2, that is, simulations are biased lower than observations for observed concentrations below 200 µg/m^3 and are biased higher otherwise.

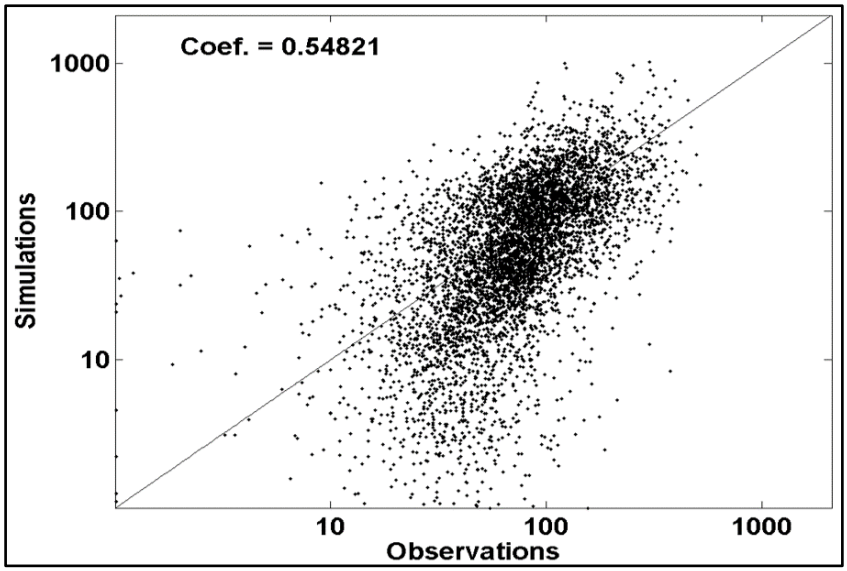

Figure 4.3 Scatterplots between simulated and observed hourly averaged PM10 dry mass concentrations (μg/m^3) for all 13 ground stations during February –April 2015.

4.3 Comparison of daily average observed and simulated PM10 dry mass

We also evaluated the model performance using the ME, RMSE and CC between the daily observed and daily modeled PM10 dry mass concentrations. Table 4.3 shows mean errors (E[Simulations – Observations]; MEs), root mean square errors (RMSEs), and correlation coefficients (CCs) of simulated daily averaged PM10 dry mass concentrations (μg/m^3) for each ground station during February–April, 2014 and 2015. MEs for most stations except stations T35, T36, and T67, are less than 4 μg/m^3. The station with maximum RMSE is T58. Correlations between simulations and observations are good for most stations, where CCs are ranged from 0.4 to 0.9. It indicated that daily simulated performed better than hourly simulated when compared to the ground-based measurement.

Table 4.3 MES (E[Simulations – Observations]), RMSES, and CCS of Simulated daily averaged PM10 dry mass concentrations (μg/m^3) for each ground station during February–April, 2014 and 2015.

Stations	**2014**			**2015**		
	ME	**RMSE**	**CC**	**ME**	**RMSE**	**CC**
T35	-7.5364	27.9224	0.812	6.7065	33.6564	0.7918
T36	5.4805	29.1970	0.8199	-5.0184	34.3066	0.7826
T37	-2.8691	38.6323	0.6489	4.5266	35.1473	0.7424
T38	-3.7546	27.9512	0.558	0.2381	25.3838	0.7799
T39	-	-	-	0.6751	31.8611	0.7995
T40	1.6133	26.7448	0.8171	-2.9505	33.1883	0.7068
T57	2.0138	38.1456	0.7631	-2.3241	36.7292	0.8651
T58	-2.7252	64.8400	0.8329	2.3538	82.3035	0.7788
T67	-4.4290	56.9932	0.6511	3.9803	54.0862	0.6783
T68	-1.2121	35.5053	0.4424	3.8699	37.8935	0.5948
T69	-1.4783	28.935	0.7282	-3.5447	27.2436	0.7854
T70	-3.7660	35.0636	0.8091	2.9672	31.1706	0.8747
T73	-2.0491	46.1501	0.8485	3.6001	43.7358	0.9027

Figure 4.4 and Figure 4.5 compares simulated and observed daily averaged PM10 dry mass concentrations for the 13 ground stations (12 stations for 2104) for the full 3-month period of February–April for the year 2014 and 2015, respectively. We can see clearly from these figure that PM10 concentrations from the end of February to the middle of March at most stations are relatively high and exceed the value of 50 μg/m^3, which is a threshold for polluted air quality according to the World Health Organization (WHO). It indicates that the air quality in northern Thailand was severely degraded by the smoke events.

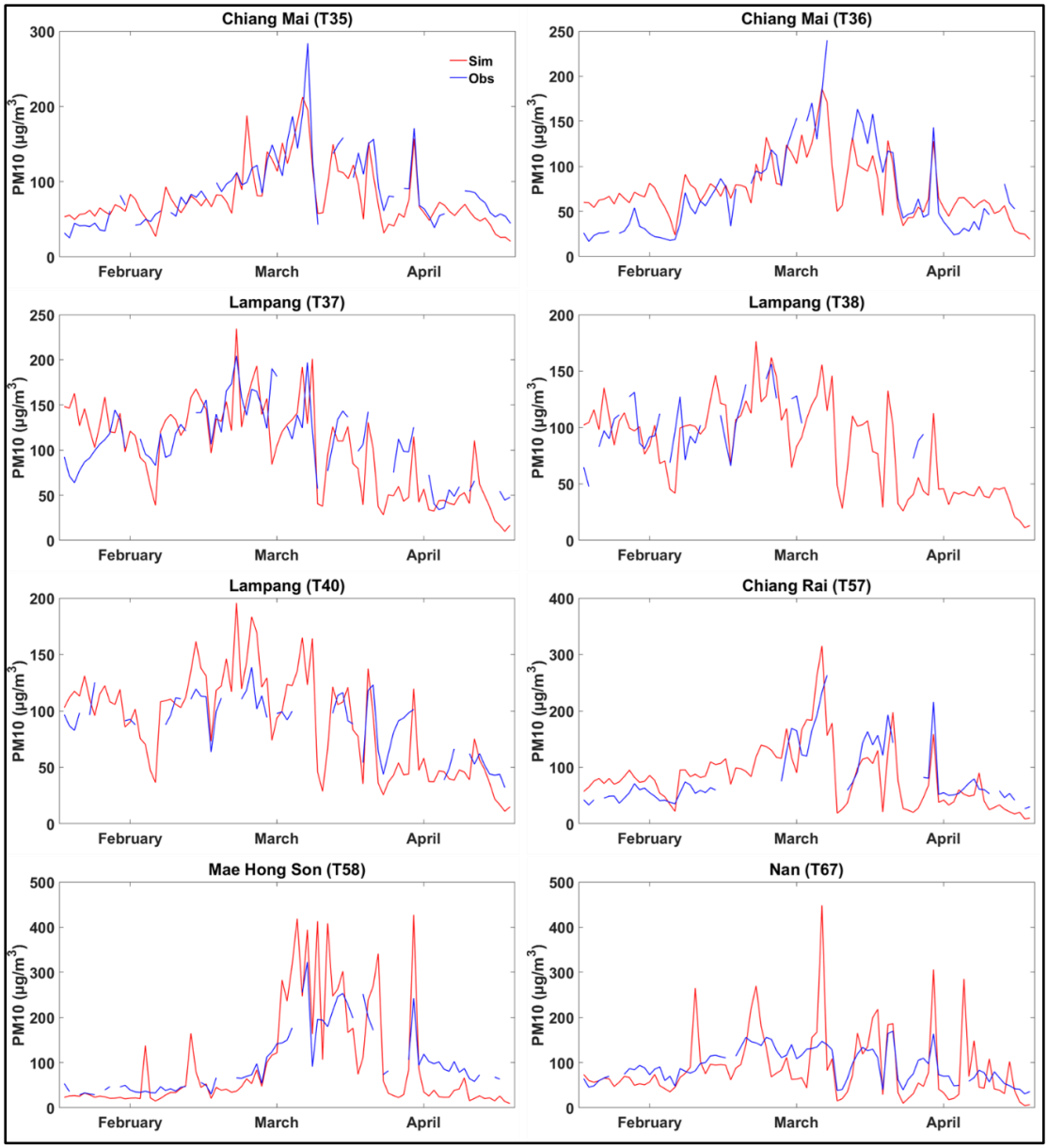

Figure 4.4 Comparisons of simulated (red) and observed (blue) daily averaged PM10 dry mass concentrations (µg/m^3) for 12 ground stations during February–April 2014. For 2014, T39 does not have data.

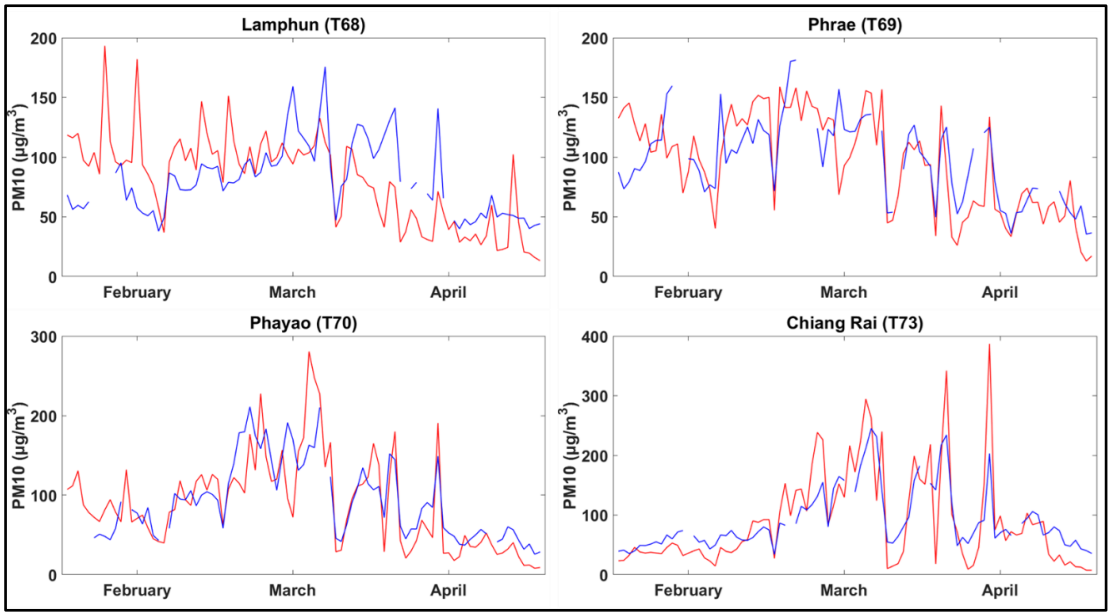

Figure 4.4 Comparisons of simulated (red) and observed (blue) daily averaged PM10 dry mass concentrations (µg/m^3) for 12 ground stations during February–April 2014. For 2014, T39 does not have data. (cont.)

During the smoke and haze period, the level of PM10 concentrations at provincial exceeded the 24-h average standard level of 120 µg/m^3 set by the PCD nearly every day start from February, with the highest PM10 levels being reached in March each year (Sirimongkonlertkul1, *et al*., 2013). To reduce air pollution, the United Nation's World Health Organization (WHO) has developed air quality standard for ambient (outdoor) PM10 levels. In any 24-hour period, PM10 should be no more than 50µg/m^3. The air pollution in northern Thailand is the cause respiratory health problems every year. Between the 9th March and 22nd March of the year 2015, Thailand's Pollution Control Department (PCD) reported the ground measurement for daily average PM10 at station T73 in Chiang Rai province ranged from 80.3 µg/m^3 to 244.9 µg/m^3 and 82 µg/m^3 to 282.6 µg/m^3, respectively, and the simulated PM10 ranged 84.3 µg/m^3 to 294.5 µg/m^3 and 86.4 µg/m^3 to 391.2 µg/m^3, respectively.

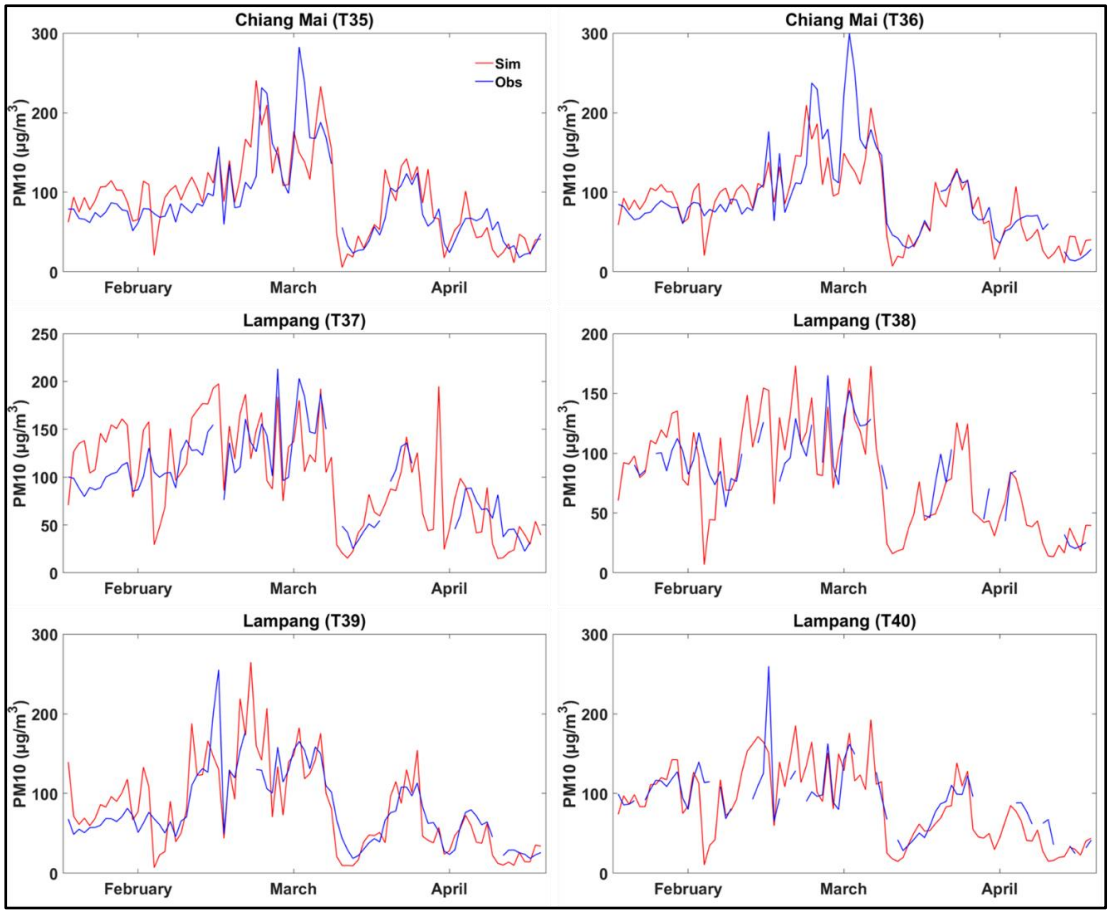

Figure 4.5 Comparisons of simulated (red) and observed (blue) daily averaged PM10 dry mass concentrations (µg/m^3) for 13 ground stations during February–April 2015.

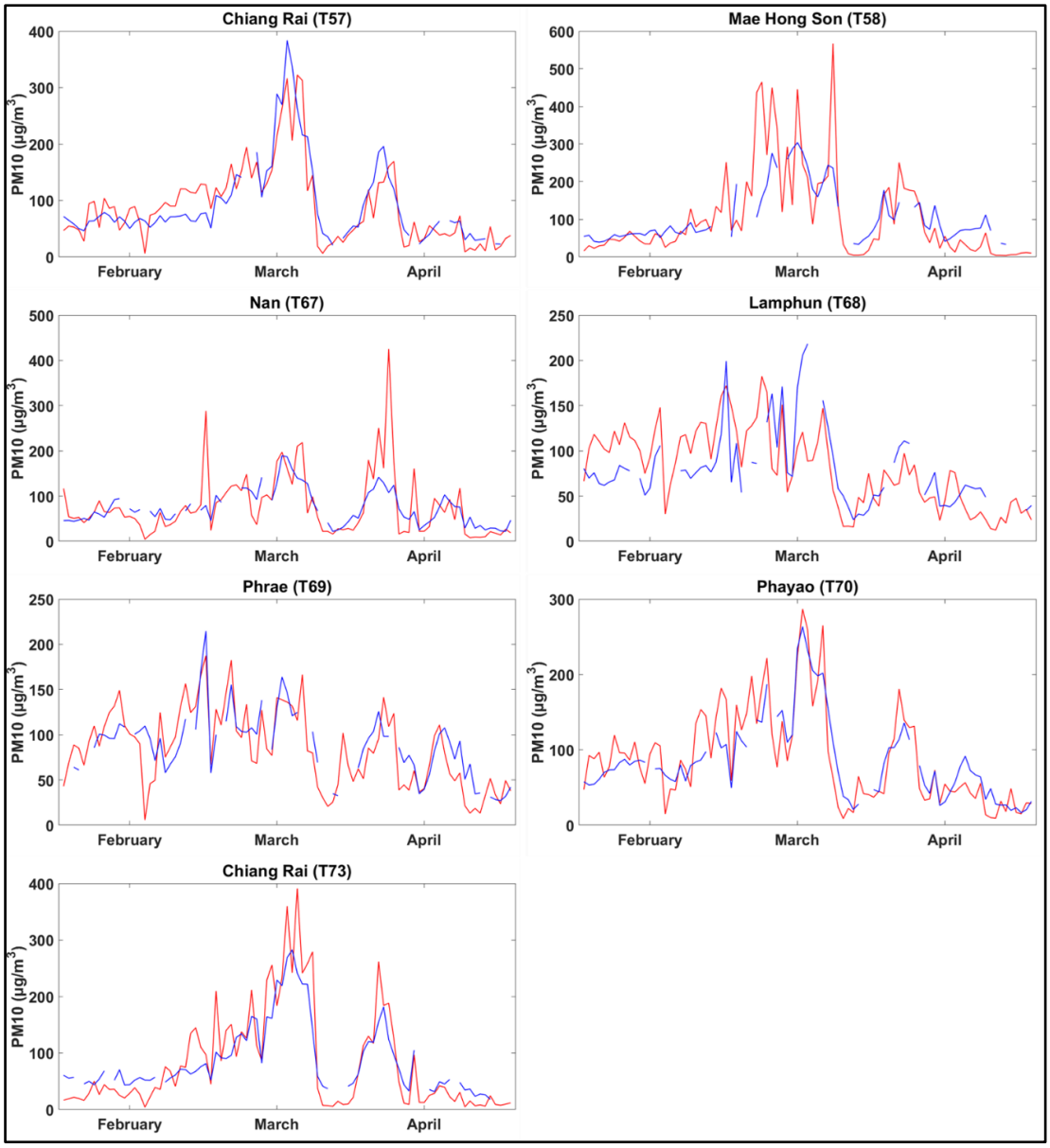

Figure 4.5 Comparisons of simulated (red) and observed (blue) daily averaged PM10 dry mass concentrations (µg/m^3) for 13 ground stations during February–April 2015. (cont.)

Figure 4.6 shows scatterplots between simulated and observed daily averaged PM10 dry mass concentrations for all 13 ground stations (12 stations for 2104) for the full 3-month period of February–April for the year 2014 and 2015, respectively. Simulations agree well with observations. The overall correlation coefficients between simulations and observations for the year 2014 and 2015 are 0.7469 and 0.7751, respectively.

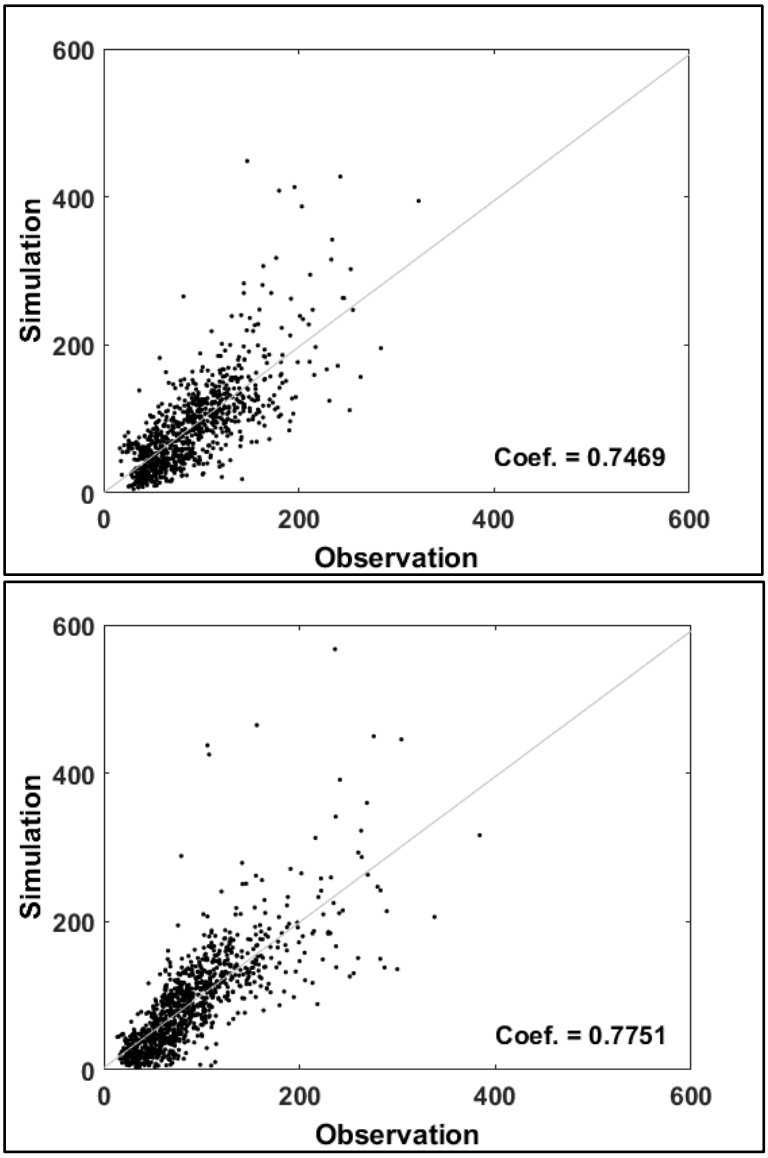

Figure 4.6 Scatterplots between simulated and observed daily averaged PM10 dry mass concentrations (μg/m^3) for all (up) 12 ground stations during February–March 2014 and (bottom) 13 ground stations during February–April 2015.

Figure 4.7 shows modelled PM10 plume (μg/m^3) 3 meter above the ground from 15th March 2015 at 01:00 UTC (or 08:00 local time) until 16th March 2015 at 00:00 UTC (or 07:00 local time) at days. Solid dots show the locations of different PM10 observation sites. In the rural and border areas, agricultural burning and forest fires, including transboundary haze from Myanmar, have contributed to high levels of PM10.

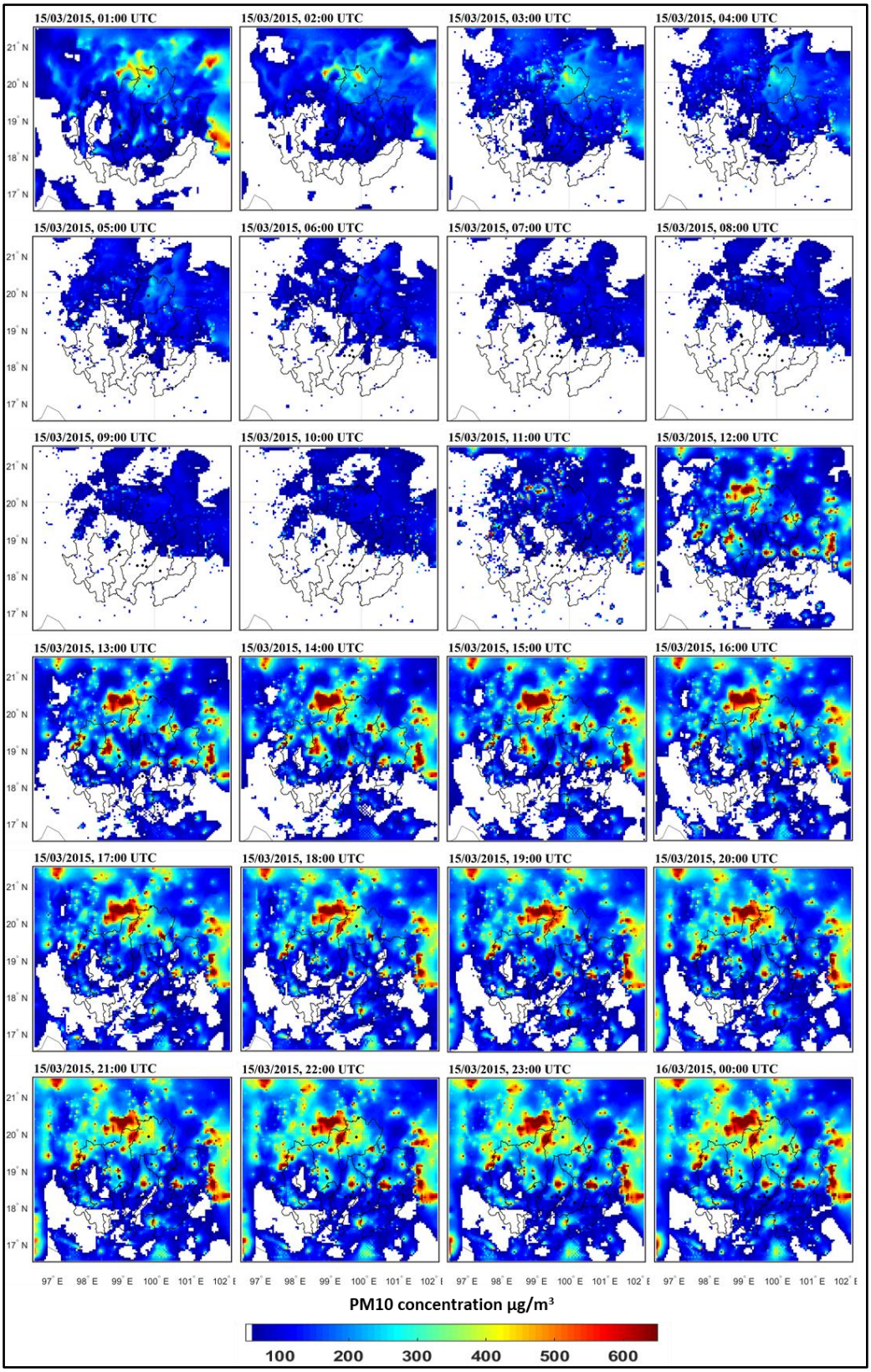

Figure 4.7 Horizontal PM10 plume ($\mu g/m^3$) at 3 meters above ground for March 15, 2015.

CHAPTER 5
CONCLUSIONS

This study analyzed the aerosol transport which is related to biomass-burning emissions from northern Thailand during the dry season (February–April) between 2014 and 2015. The simulation system is composed of the WRF/Chem model with its best physics options, global gridded analyses from the NCEP Final Analysis used for initial and boundary conditions, the RETRO and EDGAR global emission data, and the 3BEM biomass burning emission data. Simulated daily averaged PM10 dry mass concentrations at 5-km resolution for the full 3-month period of February–April of the year 2014 and 2015 were evaluated using measurements from 13 ground stations distributed in northern Thailand. Results show PM10 concentrations from late February to the mid-March at most stations are relatively high and exceeded the value of 50 $\mu g/m^3$, which is a threshold for polluted air quality according to the World Health Organization (WHO). The numerical biomass burning aerosol transport simulation system can predict the times when daily averaged PM10 dry mass concentrations are high and low well for both hourly and daily comparison. For hourly comparison, simulations have small positive biases for concentrations below 200 $\mu g/m^3$ and have negative biases for concentrations above 200 $\mu g/m^3$. The numerical biomass burning aerosol transport simulation system can provide useful simulated hourly averaged PM10 dry mass concentrations for all ranges of observed concentrations. The simulations have good utility for concentrations above 100 $\mu g/m^3$. The daily simulated performed better than hourly simulated compared to ground-based measurement with the overall correlation coefficients between the daily simulations and observations for the year 2014 and 2015 are 0.7469 and 0.7751, respectively.

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