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Article

Long range transport of Southeast Asia PM2.5 pollution to northern Thailand during high biomass burning episode

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Abstract: This paper aims to investigate the airflow that can transport emission sources of $PM_{2.5}$ from neighboring countries to contribute to air pollution in northern Thailand. We applied the coupled atmospheric and air pollution model which is based on the Weather Research and Forecasting Model (WRF) and a Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT). The model output was compared to the ground-based measurement from Pollution Control Department (PCD) to examine model performance. As a results of model evaluation, the meteorological variables fairly agreed well compared to observation with Index of Agreement (IOA) in ranges of 0.57 to 0.79 for temperature and 0.32 to 0.54 for wind speed, while the fractional bias of temperature and wind speed were 1.3 to 2.5 °C and 1.2 to 2.1 m/s. Burma was a country that contributed much of hotpot locations by 37% of the entire hotspot locations of Southeast Asia in March. The influence of Asian Monsoon can bring pollutants from neighboring countries such as Burma and Laos toward northern Thailand in March that likely contribute to high concentrations of PM2.5 in northern Thailand.

Keywords: $PM_{2.5}$, biomass burning, long-range transport of $PM_{2.5}$, Source of $PM_{2.5}$

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1. Introduction

Air pollution is a widespread problem that affects human health and other atmospheric aspects in many parts of the world. It is released from a number of man-made and natural sources including fossil fuels in electricity, transportation, industry and households, agriculture, and waste processing. According to a 2014 WHO report the premature deaths of about 7 million people worldwide were caused by air pollution (WHO, 2014). It was estimated that in developing countries approximately 300,000 to 700,000 people can be prevented from premature death if aerosol levels are reduced to a safety level (Seinfeld and Pandis 2006). Aerosol also has a direct effect on radiative forcing through the dispersion and absorption of sunlight. It can also function as a cloud condensation nucleus to change the microphysics and cloud lives, thus indirectly changing the radiative force and hydrological circulation. The global biogeochemical balance on an unprecedented scale was markedly disrupted in recent decades by dramatic human activities caused by rapid industrialization, urbanization and motorization. The Effect Environment and climate change human activities have become increasingly important and aerosol research has become a major aspect of atmospheric science.

Southeast Asia is a region with air pollution problems frequently every year, particularly at the beginning of the year, from January to April. This is because of various reasons: a lack of rain means that dust particles can potentially irritate the air even in the most polluted areas and there is smoke from burning paddy fields. In northern Thailand, all these factors are combined. There's a lot to do with geography. Mostly cities in northern Thailand located in the mountainous area which are surrounded by paddy fields. Larger villages like Chiang Mai have increased problems with traffic congestion, but farmers are also burning stubbles ready for coming rain, rice planting, at this time of the year and these narrow valleys are making perfect bowls for this smog and smoke.

Long-range transport of pollutants in the mesoscale range generally means transport across spatial scales. With regard to the annual smoke haze issue in the dry season in Northern Thailand, the main cause is from open burning, including forest fire and agricultural waste. This problem of air pollution causes severe cultural, environmental, and health degradation. Poor air quality has a rise in the concentration of air pollutants both in the form of particulate substances and gaseous such as CO, NOx, and Particulate Matter (PM). Furthermore, secondary contaminants, including ozone (O3), which is harmful to human health and vegetation. The contributing pollutants in Northern Thailand, however, are not only from national sources but from transporting long distances of air pollutants (Kim Oanh and Leelasakultum, 2011). Trajectories are well known for being strong indicators of large flow and can be helpful in the study of possible regional sources. The term "fine particles" or 2.5 (PM2.5) refers to smaller particles or droplets in the air, two and a half microns or less. Unlike centimeters, meters, and miles, a micron is a unit of distance measurement. It's about 25.000 microns in an inch. The diameter of the larger PM2.5 particles will be around thirty times smaller than that of human hair. Particles in the PM2.5 range are able to penetrate deeply into the respiratory tract and enter the lungs. Exposure to small particles can also impair the function of the lungs and exacerbate medical conditions such as asthma and heart disease. Fine particles are also formed by the reaction of gasses or droplets in the atmosphere from sources such as power plants. These chemical reactions may occur miles from the source of the original emission. Resulting of the high of PM2.5 in Chiang Mai which is one of Thailand's largest cities, reached 380 on the Air Quality Index (AQI) making the northern city is one of the most polluted cities in the world.

Since PM2.5 is the most important air pollutant and strong effects on human health, so there were previous studies about PM2.5 using both instrument and modeling in northern Thailand. For example, Vichit–Vadakan et al. (2001) conducted three-panel studies in Bangkok to determine the statistical relation between PM2.5 levels and respiratory symptoms. Tsai et al. (2000) researched on indoor and outdoor PM10 and PM2.5 in Bangkok, while Jinsart et al. (2002) examined the roadside PM2.5 and PM10-2.5 levels. More informative studies emphasized on different sized fractions in order to understand their sources of origin. Chueinta et al. (2000) reported the characterization and source identification of fine and coarse particles collected in urban and suburban residential areas in Thailand and an extended study at Bangkok metropolitan curbside was later performed (Chueinta and Bunprapob, 2003). Leenanupan et al. (2002) carried out similar work for the characterization of fine particulate pollution at Mae Hong Son province in the north of Thailand. A few collaborative studies on fine and coarse particulate air pollution in the Asia Pacific regional scale were reported, e.g., Oanh et al. (2006); Ebihara et al. (2006; 2008); Hopke et al. (2008). Besides, only a few long–term PM2.5 and PM10-2.5 monitoring data are available elsewhere in this region.

This work applied the atmospheric model coupling with air pollution model to study the effect of biomass burning and anthropogenic emission on PM10 concentration. We used the Weather Research and Forecasting (WRF) model version 3.8.1 to simulate the meteorological conditions in March 2012. The model's initial and boundary conditions are from the Final Analysis Data (FNL) (NOAA/NCEP, 2000). The modeled temperature and wind speed were compared to the dataset from the Pollution Control Department (PCD). To clarify the model capability, statistical metrics such as Index of Agreement (IOA) and Fractional Bias FB were used for the model evaluation. The output from the WRF model was used as meteorological conditions into the HYSPLIT model to find out the long-range transport of regional air pollutants from neighboring countries of Southeast Asia toward northern Thailand.

2. Experiments

2.1 Model configuration

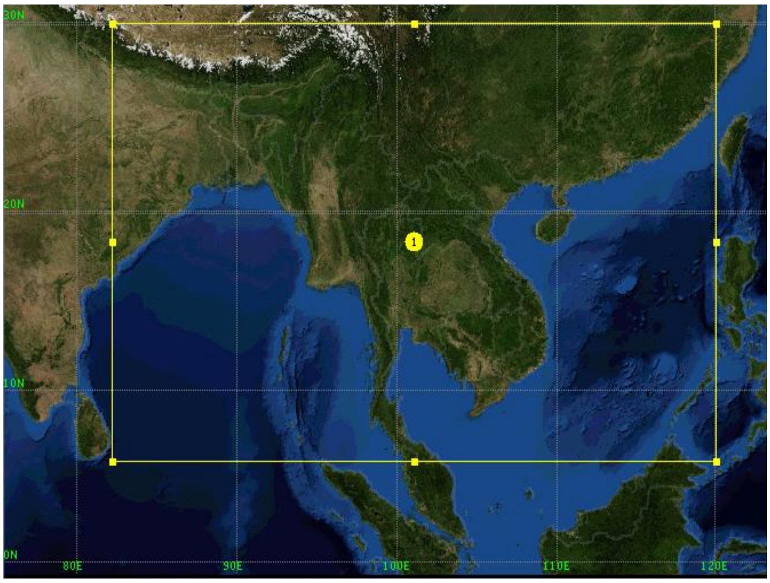

Figure 1 Domain configuration

We use a coupled atmospheric model called WRF model version 3.8 (Skamarock et al., 2008) and an air quality model called the HYSPLIT model to generate meteorological input into HYSPLIT. The results from HYSPLIT were then used to identify the PM2.5 pathway in Southeast Asia. The WRF model has been developed to study several atmospheric studies and also to be used for operational weather forecasting. It is a non-hydrostatic mesoscale model consisting of a number of physical schemes, including radiation, cumulus, and microphysics. While the HYSPLIT model is based on a Lagrangian calculation to address the air pollutant trajectory and concentration. It combines two computational approaches, i.e. 3D-particles and puffs, to calculate the concentrations of the pollutants. In this study, we are designing 1 WRF domain with a horizontal resolution of 20 km grid spacing. In addition, the model set 30 vertical levels up to 50 hPa. The outer domain covers entirely the upper mainland of Southeast Asia and some areas of East and South Asia, such as the South of China and East of India, as shown in Figure 1. Southeast Asia is influenced by East Asian monsoon, which carries air mass from high latitudes to this region. The transboundary emission from the western border, such as Myanmar and India, also affects the quality of the air in northern Thailand. While the inner domain is in northern Thailand. In order to solve the water vapor, cloud, and precipitation process, the model was configured using the WRF Single-Moment 3-class scheme followed by Hong et al . , 2004; Hong and Lim 2006. It predicts a simple-ice system with three types of hydrometers, i.e. vapor, cloud water, and rain. The calculation of these processes is based on the mass content of the diagnostic relationship. The Kain-Fritsch scheme (Kain, 2004) is the sub-grid scale process for convective resolution. It has the potential to use a cloud model with updrafts and downdrafts, as well as to consider the effects of detrainment and training on cloud formation. The similarity theory scheme is used to emulate thermal gradient over the surface responsible for friction velocity and wind over the surface (Paulson, 1970; Dyer and Hicks, 1970; Webb, 1970; Beljaars, 1940; Zhang and Anthes, 1982). The model spin-up was conducted from 15 – 28 February 2012 to reduce the effect from initial conditions. From March 1, 2012 – April 1, 2012, the WRF model was designed to simulate the weather conditions for the HYSPLIT model. The main meteorological variables of the WRF model, i.e. wind (U, V, W), temperature (T), surface pressure (Psfc) and relative humidity (RH), were used as input data for the HYSPLIT model.

Table 1 Physics option in model configuration

Scheme	Option
Microphysics	WSM 3-class simple ice scheme
Radiation	rrtm scheme
Surface Phyaics	Duhia

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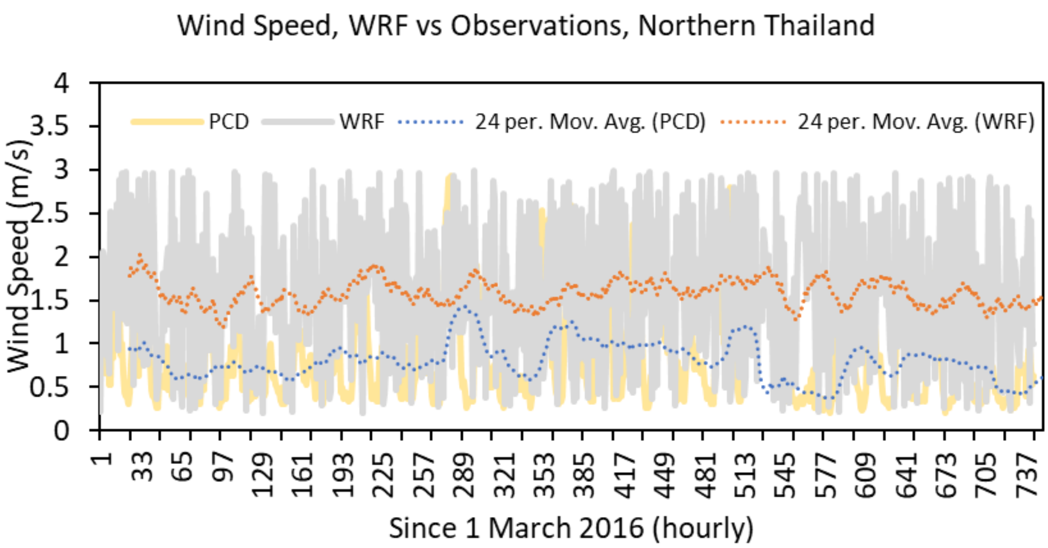
Boundary Layer	NOAH
Convective	Kain-Fritsch (new Eta) scheme

3. Results & discussion

To quantify long-range transport from Southeast Asia to Thailand, we begin with a model assessment to examine the performance of the model. We then analyzed the hotpot location in South East Asia using the MODIS satellite dataset based on TERRA and AUQA. The next section is to see the impact of mesoscale meteorology on the smog problem in northern Thailand. Finally, we used a backward trajectory analysis in the HYSPLIT model to find the source location of the smog problem in northern Thailand.

1.1 Model Evaluation



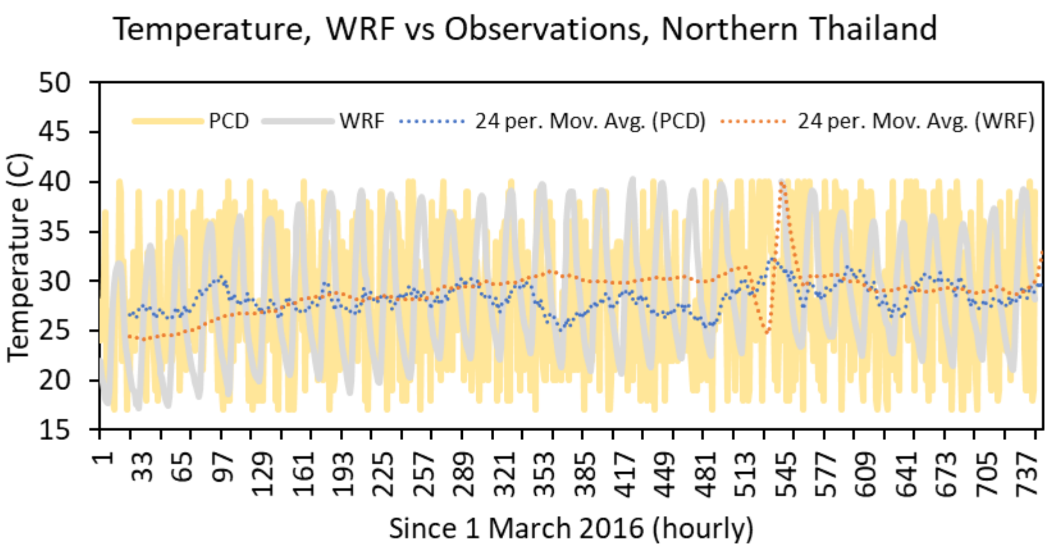


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Figure 2 Averaged wind speed and temperature between 1-hourly WRF model output (gray) and hourly observation from PCD (yellow) and 24-hourly WRF model output (orange-dot) and 24-hourly observation from PCD (blue-dot)

Table 2 Statistical analysis between WRF model and ground-based measurement

	Temperature		Wind speed	
Station	IOA	FB	IOA	FB
Chiang Mai	0.79	2.5	0.54	2.1
Lampang	0.66	1.3	0.46	1.5
Nan	0.57	2.4	0.32	1.2

Table 3. Location of PCD measurement in northern Thailand

Location	Latitude	Longitude
Nan	18.78	100.77
Lampang	18.25	99.76
Chiang Mai	18.78	98.98

In order to examine the model capability, we compared the model results from the WRF model to the ground-based observations from the Pollution Control Department (PCD) as shown in Table 3. In general, Thai PCD measures the hourly concentrations of six pollutants: PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, and O_3. The PCD measurement sites almost locate urban areas nearby. It is likely to be influenced by the emission of motor vehicles. Since PCD has recently measured $PM_{2.5}$ in Thailand, there are coupled station sites with a PM2.5 dataset. Here, we compared the modeled results to the PCD dataset at 3 locations, which is based on the complete $PM_{2.5}$ dataset as shown in Table 3. We used the statistical indicator, that is. Index of Agreement (IOA) and Fractional Bias (FB) to examine the efficiency of the model.

The comparison between the hourly output of the model and the observation data is shown in Figure 2. In general, the model captures well in comparison to the observation. The modeled temperature at 2 m is slightly higher than the ground-based measurement by 2 – 3 ° C, while the wind speed is overestimated by 1 m / s. In addition, the statistical analysis shown in Table 2 shows that the WRF and PCD data set agree well on hourly temperature and wind speed for most sites with acceptable IOA in the ranges of 0.57 to 0.79 for temperature and 0.32 to 0.54 for wind speed. However, the model generally overestimates the temperature of 1.3 – 2.5 C and the temperature of 1.2 – 2.1 m / s indicated by Fractional Bias (FB). The key possibility of error is likely to arise from the rough resolution of the 20 km grid spacing model simulation, which is difficult to simulate sub-grid scale processes such as convection and wind, in particular the simulation of winds requiring correction of the Large Eddy Simulation (LES). As discussed in Wurp et al., 2020, a good LES simulation corresponds to very fine resolution, e.g. 2.5 m, 10 m, and 20 m.

3.2 Hot spot analysis

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We have used Near Real Time (NRT) Moderate Imaging Spectroradiometer (MODIS) hotpot position data to evaluate the Southeast Asian fire situation. A 1 km pixel center with the MODIS Fire and Thermal Anomaly Algorithm (Giglio et al . , 2003) as comprising one or more fires is the thermal / active fire. This is the simplest fire substance that detects active fires and other thermal phenomena, including volcanoes. The January to April 2016 fire hotspot data is obtained via the https:/firms.modaps.eosdis.nasa.gov/ fire information for the resource management system (FIRMS).

Table 4 showed the number of fire hotspot locations in Southeast Asia between January and April 2016. From January to April, the number of hotpot sites has steadily increased 3 times. Cambodia contributes a significant amount of hotpot location by > 10,000 in January and March, representing approximately > 40 % of the total hotpot in south-east Asia, while the Burma and Laos countries were the major contributors to hotpot locations by 23,132 and 24,570 in March and April, representing approximately 37% and 28% of the hotpot location in Southeast Asia as mentioned in Table 4. In fact, the hotspot position in Thailand rises by 5 times between January and March. When we focus on hotspot locations in northern in March, found that it contributed about 30 % of the entire hotpots of Thailand that Mae Hong Son province was the most contributor to hotpot location as listed in table 5. The hotspot in Thailand, however, is about 16% lower than in Burma 2 times, while Laos still contributes around 18%. Hotpot locations in neighboring countries and Thailand are growing at average monthly $PM_{2.5}$ concentrations in northern Thailand, which also continually increase to 70 μg/m^3 from October 2015 to March 2016 (Figure 4). The highest concentration of $PM_{2.5}$ was approximately 96 μg/m^3 on 20 and 24 March 2016 in northern Thailand. This report would possibly tell us that hotpot sites in neighboring counties near Thailand are the major sources in northern Thailand in March of high $PM_{2.5}$ concentrations.

Table 4 Number of hotspot location in Southeast Asia between January and April 201

Country	January	February	March	April
Indonesia	3,295	933	1,899	1,524
Burma	1,507	4,643	23,132	19,013
Cambodia	10,149	11,408	6,763	6,841
Laos	497	1,855	11,284	24,570
Thailand	2,580	5,730	10,275	7,819
Vietnam	1,520	2,612	5,357	5,094
Philippines	756	736	2,344	2,318
Malaysia	288	306	1,195	1,535
Total	20,609	28,221	62,260	68,730

Table 5 Number of hotspot location in northern Thailand in March 2009

Province	No. of Hotspot
Chiang rai	196

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Chiang Mai	566
Nan	326
Phayao	147
Phrae	471
Mae Hong Son	795
Lampang	461
Lamphune	97
Total	3,059

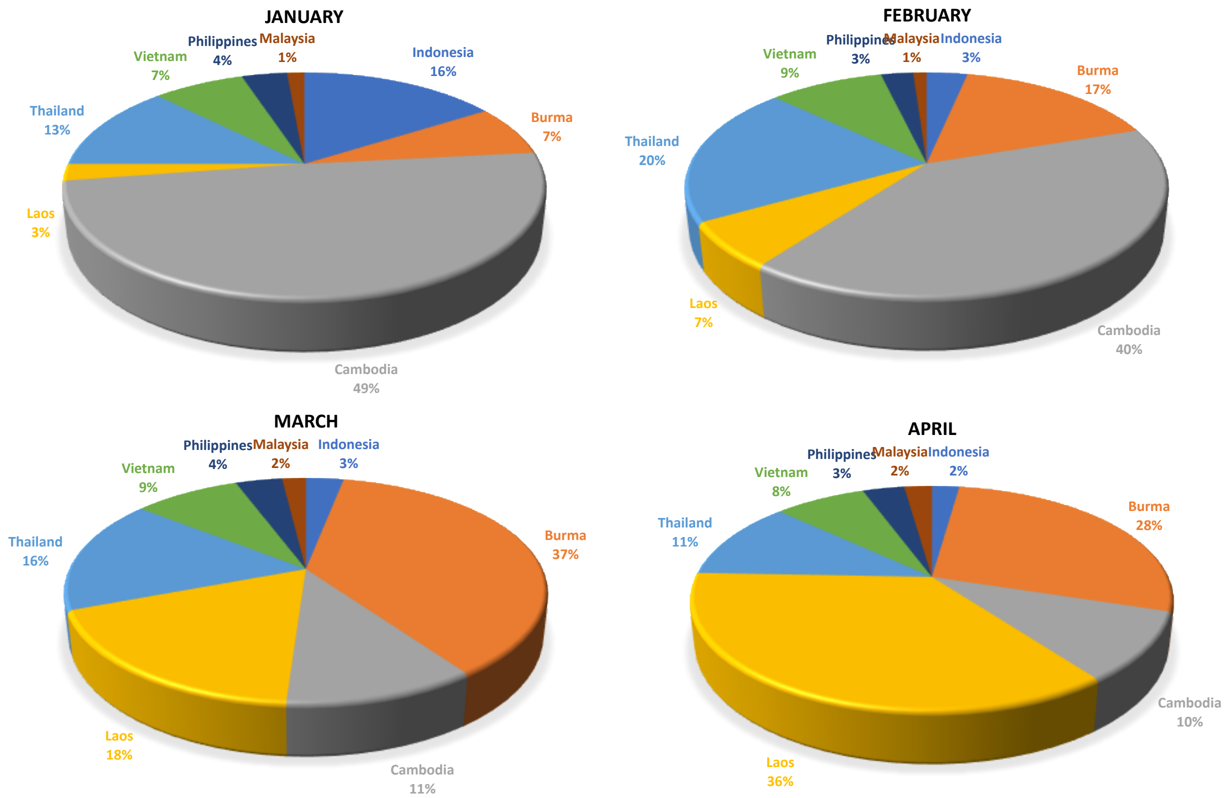

Figure 3 The proportion of hotspot location of each country in Southeast Asia

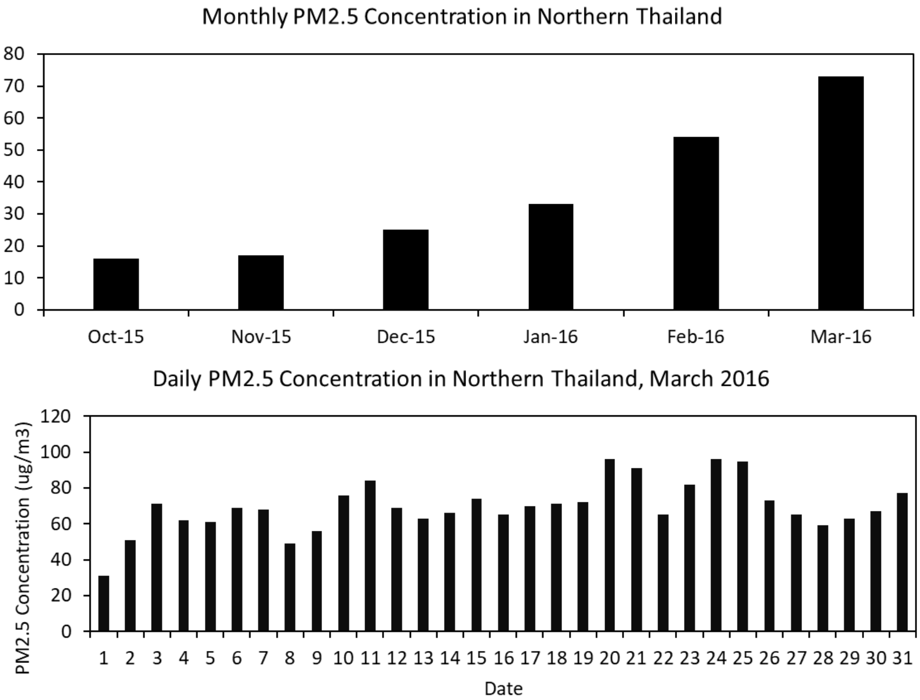

Figure 4 Monthly and daily of $PM_{2.5}$ concentration in March 2016 in northern Thailand

1.2 Relationship between meteorological factor on $PM_{2.5}$

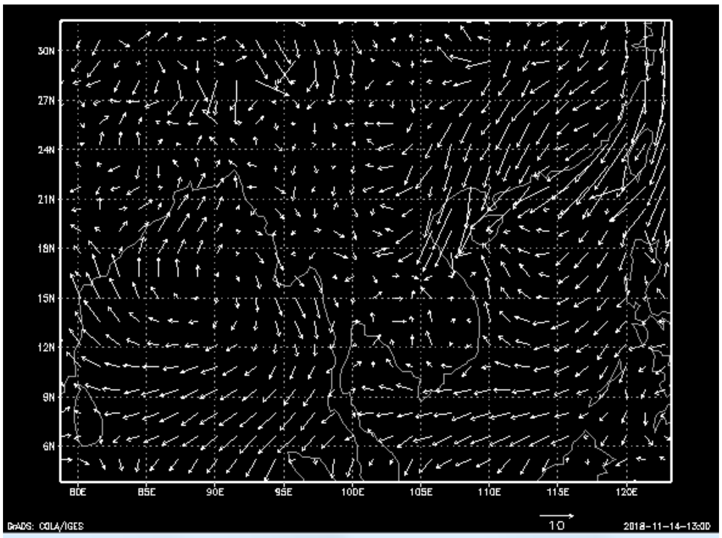

Figure 5 Averaged wind speed and direction from WRF model in March 2009

The Asian Winter Monsoon, which occurs from November to March, circulates air from mainland Asia towards the oceanic regions. During March 2016, the winds entered the north of Thailand through two major channels (Figure 5). The first channel is characterized by winds blowing from eastern Asia (e.g., eastern China and Taiwan) toward Laos and northern Thailand, while the second channel is characterized by northwesterly winds blowing from Burma and entering into northern Thailand. These flow patterns indicate that northern Thailand is influenced by emissions from a wide range of biomass burning sources located in Laos and Burma. The winds blowing through the first and second channels will also bring trace gases and aerosols emitted from the biomass burning activity in Laos. Thus, northern Thailand is affected by biomass burning sources.

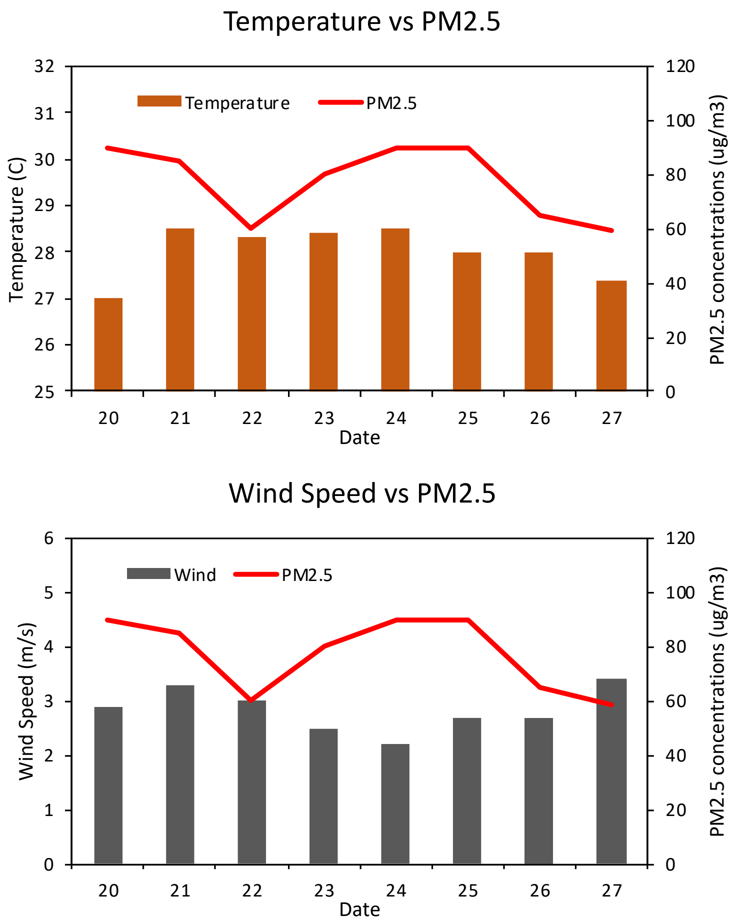

Figure 6 Relationship between temperature and $PM_{2.5}$ (up) and Wind Speed and $PM_{2.5}$ (low)

Table 6 Relationship between wind and temperature, and PM2.5 in northern Thailand in March 2006.

	R	R_s
Wind vs PM2.5	0.082	-0.53
Temp vsPM2.5	-0.46	0.18

Since the atmosphere is a very complicated component, a linear and non-linear analysis may be necessary to analyze the relationship of each factor in the atmosphere. Data from $PM_{2.5}$ and meteorology, such as temperature and wind, were used by the Pollution Control Department (PCD) to analyze the relationship between the weather factor and $PM_{2.5}$ during 20-27 March 2016, which shows a high concentration of $PM_{2.5}$ in northern Thailand. In this section, we used both linear and non-linear correlation analyses to see the relationship. The linear analysis of the correlations was based on the Pearson correlation (1), while the non-linear correlation was based on the Spearman equation (2).

Pearson's correlation coefficient.

$$r_{x,y} = \frac{?x_i y_i - n\bar{x}\bar{y}}{(n-1)s_x s_y} \qquad (1)$$

$$s_x = \sqrt{\frac{1}{n-1} ?_{i=1}^{n} (x_i - \bar{x})^2}$$ and analogously for s_y, $$\bar{x} = \frac{1}{n} ?_{i=1}^{n} x_i$$

n *is sample size and* x_i, y_i *are the individual sample indexed*

Spearman Equation;

$$r_s = 1 - \frac{6 ? d_i^2}{n(n^2-1)} \qquad (2)$$

d_i is the difference between the two ranks of dataset, n is the number of datasets.

In general, the linear correlation analysis shows a slightly positive wind speed coefficient and a negative temperature coefficient of 0.082 and (-0.46) (Table 6). Non-linear correlation analysis shows a negative wind speed correlation with (-0.53) but a slightly positive temperature correlation with 0.18. Linear and non-linear correlation analyzes indicate that biomass burning is negative in relation to precipitation and carbonaceous aerosol by (-0.51) and (-0.67) (Table 6). Look at Figure 6, it shows a certain relationship between temperature and wind and a high concentration of PM2.5 during 23-26 March 2016. When the concentration of PM2.5 gradually increased from 60 µg / m3 on 23 March to 90 µg / m^3 on 25 March, the temperature also decreased slowly from 28.5 °C on 23 March to below 27 °C on 25 March. At the same time, wind speed is also reduced from 3 m / s to 2.5 m / s. These results make any sense in the context of meteorology affecting the quality of the air. Because low temperatures can suppress near-surface air pollution, while low wind speeds deteriorate air quality relative to near-ground pollutants due to limited air ventilation (Jones et al., 2010).

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1.3 Backward air mass trajectory analysis

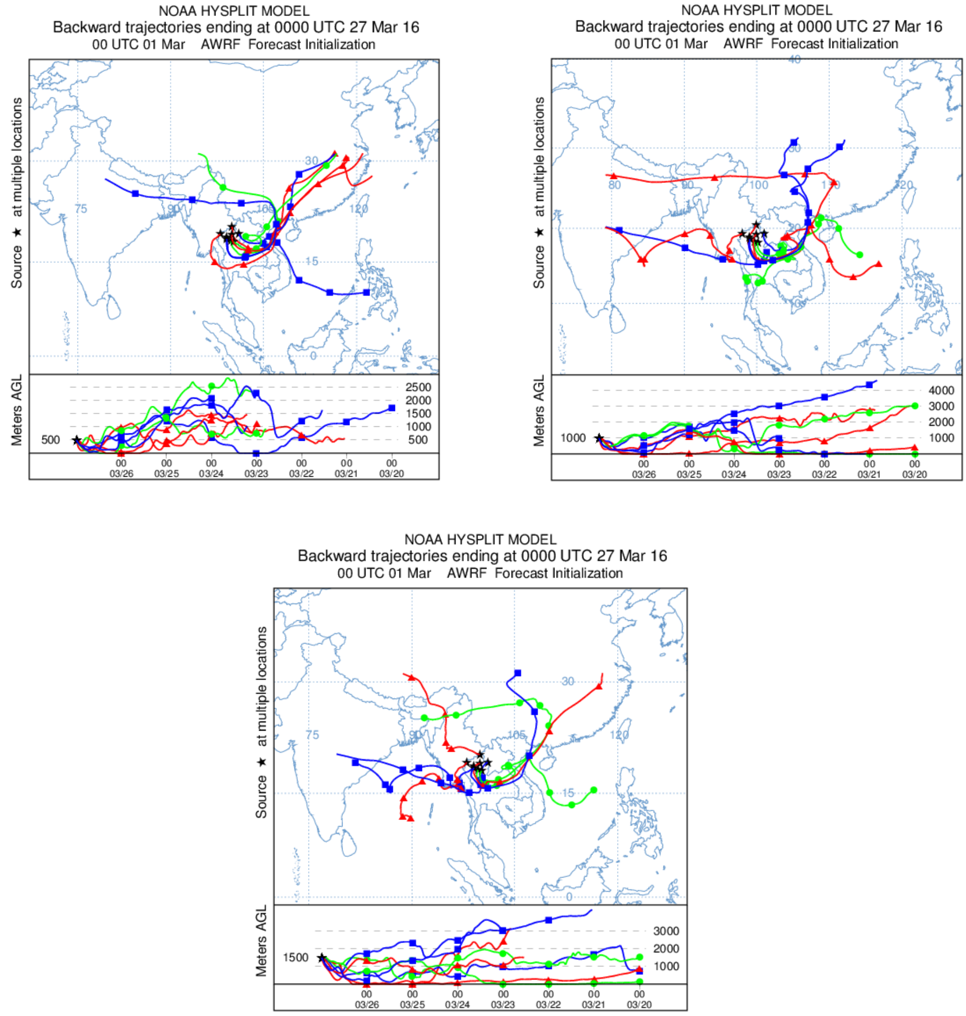

Figure 7 HYSPLIT backward ensemble trajectories initiated at a)500m, b)1000 m, and c) 1500 m on 27 March 2016 in northern Thailand

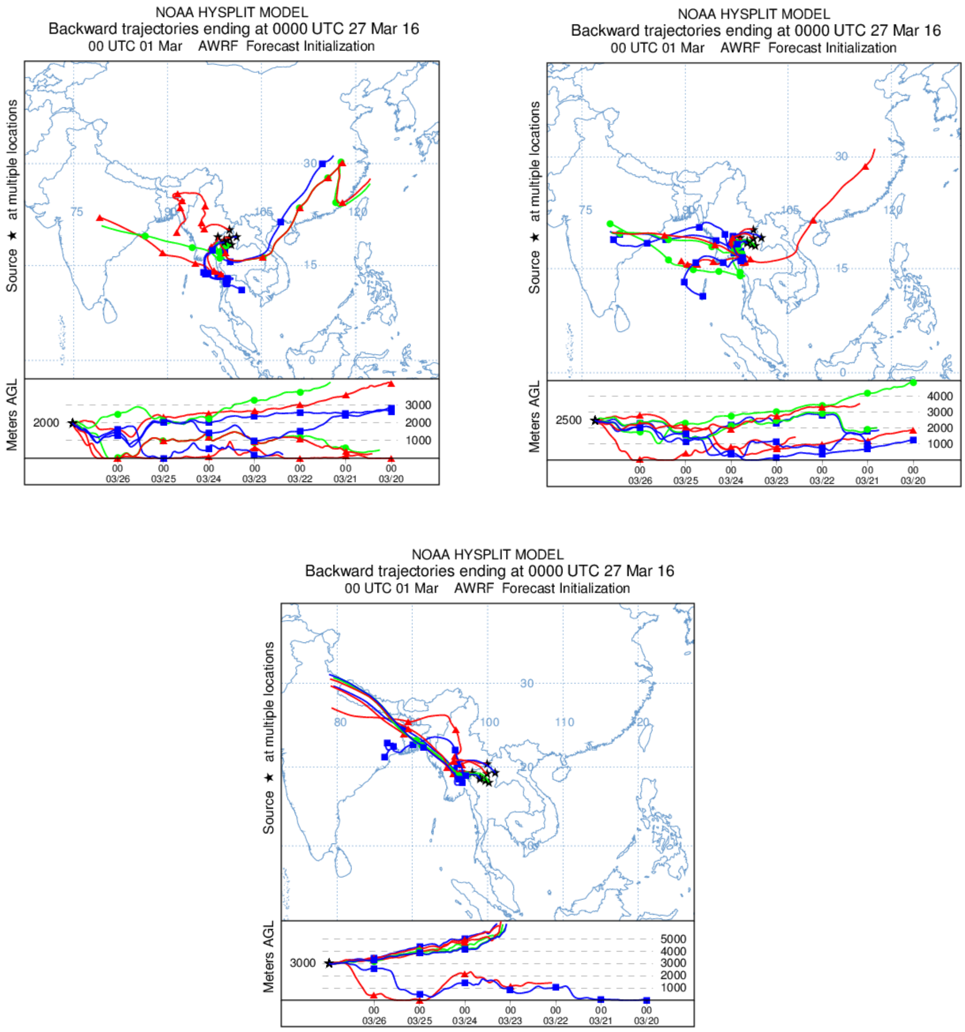

Figure 8 HYSPLIT backward ensemble trajectories initiated at a)2000m, b)2500 m, and c) 3000 m on 27 March 2016

HYSPLIT trajectory plots with eight trajectories were generated for the period 20 to 27 March 2016, as shown in Figures 7 and 8. In time, the trajectories were calculated for backward. The backward trajectories started above eight locations, which are based on 8 provinces of northern Thailand at altitudes ranging from 500 m to 3000 m. In general, the north-eastern monsoon affected the north of Thailand. The backward trajectory map showed that the air mass that reached northern Thailand originated in the northeast. The winds were of continental origin and were picked up during the day. Another channel is from the northwest airflow, with the backward trajectory map showing that the air mass reaching northern Thailand originated in Burma and some parts of India. At 500 m, the airflow from the north-east is over northern Thailand, which is likely to bring some pollutants from eastern China, northern Vietnam, and Laos to the north of Thailand. While at 3000 m it is clear that transport from Burma and India strongly dominates the emission sources of pollutants to the north of Thailand.

4. Conclusions

This paper aims to understand the role of regional transport of air pollutants results in high PM2.5 in northern Thailand during high biomass burning emission in March 2016. We conducted a coupled atmospheric and air pollution modeling system which is based on the Weather Research and Forecasting Model and a Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT). The WRF model was performed with 1 domain of 20 km grid spacing covers Southeast Asia, some parts of India, and China. Final analysis data was used as a meteorological initial and boundary condition. The model results including temperature and wind speed were compared to the ground-based measurement from the Pollution Control Department (PCD) in northern Thailand. Model's capability is acceptable when compared to observation which was indicated by Index of Agreement (IOA) in ranges of 0.57 to 0.79 for temperature and 0.32 to 0.54 for wind speed, while the fractional bias of temperature and wind speed were 1.3 to 2.5 °C and 1.2 to 2.1 m/s. We analyzed the hotspot data from Near Real Time (NRT) Moderate Imaging Spectroradiometer (MODIS) to find out the proportion of hotspot in Thailand and neighboring countries in Southeast Asia. The results found that a number of hotspot locations in Burma is greater than Thailand by 2 times cooperated with the influence of two major channels of Asian Monsoon including easterly and northwesterly wind brought pollutants from neighboring counties toward northern Thailand. This finding was confirmed by backward trajectory analysis. It showed that the air mass that reached northern Thailand originated in the northeast and northwest airflow which was originated from Burma.

Author Contributions: Teerachai Amnuaylojaroen: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Jirarat Inkom: Contributed reagents, materials, analysis tools or data

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

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