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Dispersion Modeling of SO_2 Emissions from a Lignite Fired Thermal Power Plant using CALPUFF

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Abstract

In this work, dispersion of sulfur dioxide (SO_2) in the vicinity of Mae Moh power plant, the largest fossil fuel power plant in northern Thailand, was investigated using well known air dispersion model. The area of 2,500 km^2 around the plant was studied, with spatial resolution of 200 x 200 m^2. Publicly available MM5 and CALMET software were used to provide meteorological conditions within the study domain, while CALPUFF was used to simulate the patterns of SO_2 dispersion, based on actual plant operations in winter, summer and rainy seasons of the year 2009. Comparison against measurements from monitoring stations was made. Simulated results were found to agree qualitatively and quantitatively well with measured data. Root mean squared errors were found in the range between 2.19 to 8.32 $\mu g/m^3$. The CALPUFF model can be used for SO_2 dispersion prediction with satisfactory accuracy.

Keywords: air pollution, CALPUFF, coal power plant, dispersion modeling, Mae Moh

1. Introduction

Over 75% of Thailand's total annual lignite production comes from Mae Moh open-pit lignite mine, located in northern Thailand. All of them are consumed by Mae Moh power plant, producing electricity to serve about 10% of the total electrical energy demand in the country. Ten production units of Mae Moh power plant comprise four units of 150 MW and six units of 300 MW. The total generating capacity is 2,400 MW, consuming lignite at approximately 17 million tons per year. Mae Moh lignite is generally of low quality, with high sulfur content (3%). Consequently, the power plant generates significant amount of sulfur dioxide (SO_2). High concentrations of SO_2 have negative impact on fauna and flora, and can produce acute injury in the form of foliar necrosis, even after relatively short duration exposure and. To reduce SO_2 emissions, flue gas desulfurization (FGD) plants have been installed to all power units since 2000 and their removal efficiencies are around 97-98% (Jonathan & Lovell, 1998). Average SO_2 emission rate after FGD was about 450 g/s. Monitoring of air pollutants is performed continuously in the area surrounding Mae Moh power plant with total of 11 stations (Jitman, 2010). From operation and management points of view, it would be good idea to predict and forecast SO_2 dispersion around the power plant when there are changes in operation of the plant, geometry of the area or local atmospheric conditions, so that measures can be implemented to prevent any harms that may arise in the future.

Since SO_2 can travel for a long distance according to wind direction and meteorological conditions, a detailed long-range transport model is needed to simulate the atmospheric processes and the resulting pollutant concentrations in the air. California puff model (CALPUFF) is one of the most popular dispersion models to study long-range pollutant transport and is recommended by the US Environmental Protection Agency (EPA) for regulatory applications (Scire et al., 2000). It is a non steady-state, Lagrangian dispersion model that provides significant improvement in atmospheric motion simulation, especially across large horizontal distances (i.e., 50 km or more) when compared to the traditional steady-state, Gaussian dispersion models.

There have been a number of works adopting CALPUFF to simulate pollutant transport and dispersion. Varna and Gimson (2002) modeled the inter suburb dispersion of particulate matter pollution in Christchurch, New Zealand using CALPUFF during a wintertime particulate pollution episode. Levy et al. (2002) applied the CALPUFF atmospheric dispersion model with meteorological data from the National Oceanic and Atmospheric

Administration's rapid update cycle model to a set of nine power plants in Illinois to evaluate primary and secondary particulate matter impacts across a grid in the Midwest, USA. Cohen et al. (2005) developed a regression model to approximate the CALPUFF predicted concentrations and to determine the impacts of roadway proximity on ambient concentrations of three hazardous air pollutants. Jiang et al. (2003) employed a back trajectory method using the CALPUFF model in a reverse diffusion mode to investigate the details of ozone formation within the Puget Sound area of western Washington state, USA. Bandyopadhyay (2009) studied ambient air quality around an industrial estate in India and predicted the ground level concentration of SO_2 under various scenarios using industrial source complex short term (ISCST3) model.

In Thailand, Doolgindachbaporn (1995) used CALPUFF with a fumigation algorithm grid model to evaluate maximum hourly, maximum daily, and average ground level SO_2 concentrations to predict the impact from Mae Moh power plant. The simulated concentrations were found to slightly overestimate the measured data. This was due to assumption of no chemical transformations and depositions of SO_2. Kanokkanjana (2004) modeled dispersion of air pollutants (SO_2, NOx, and PM10) in Laem Chabang industrial estate using ISCST3 and CALPUFF models. Good correlation was obtained between 50 predicted maximum one-hour average concentrations and observed data. However, poor correlation for all hourly data was obtained. Correlation between the ISC and CALPUFF model outputs was good between the 50 maximum concentrations. According to the time series analysis, the model outputs did not agreed well with the monitoring data because the quality of emission inventory was not appropriate for modeling. Jiruagnimitsakul (2004) used CALPUFF air quality model to sulfur dioxide emission from a coal power plant where majority of predicted concentrations agreed well with the observed values. Tuaycharoen (2006) compared the model performances between regional atmospheric modeling system (RAMS)-California meteorological model (CALMET)/CALPUFF and ISCST3. They were used to simulate the dispersion of pollutants from Khanom power plant, the biggest thermal power plant in southern Thailand. Two different seasons were simulated; during December 2004 under the influence of north-easterly monsoon, and during June 2005 under the influence of south-westerly monsoon, respectively. Simulated NOx concentrations from both models were compared. The RAMS-CALMET/CALPUFF was shown to perform better than the ISCST3 model. Patima (2006) investigated SO_2 dispersion in Laem Chabang industrial complex using CALPUFF. Gas dispersion in this area was influenced by prevailing wind and atmospheric conditions

In this work, CALPUFF was utilized to predict SO_2 dispersion around Mae Moh power plant. Seasonal variation was simulated for January, March and October 2009, representing winter, summer and rainy seasons. Comparison between the model simulation and the measurement results from monitoring stations was performed to evaluate prediction accuracy for high and low concentration episodes of SO_2.

2. Methodology

2.1 Study Domain

In this study, dispersion of SO_2 emitted from the power plant over Mae Moh basin was evaluated. The entire study domain (50 km x 50 km) is shown in Figure 1, with the power plant positioned at the center. The southwest corner of the domain is located at longitude 99.5E, latitude 18.1N. The northeast corner is located at longitude 100.0E, latitude 18.5N. There are 11 receptor points in both the X and Y directions, with a square grid spacing of 200 m. All 11 monitoring stations are indicated in Figure 1, surrounding the power plant. Their names and locations are given in Table 1.

Table 1. Locations of 11 monitoring stations of the Mae Moh power plant

Monitoring Station	UTM GRID East	UTM GRID North	MSL
Pratupha army camp (PC)	586.046	2043.679	482
Ban tha si (TS)	580.337	2037.274	384
Ban sa det (SD)	565.683	2033.116	268
Ban hua fai (HF)	578.475	2032.540	345
Main station (MS)	578.035	2022.430	318
EGAT housing ban huai king (HK)	572.544	2023.589	408
Government center (GC)	569.648	2021.036	409
Ban sop moh (SM)	575.408	2018.573	348
Ban sop pad (SP)	580.976	2017.365	342
Ban mae chang (MC)	583.604	2020.914	332
Ban mai ratanakosin (RS)	590.494	2025.471	365

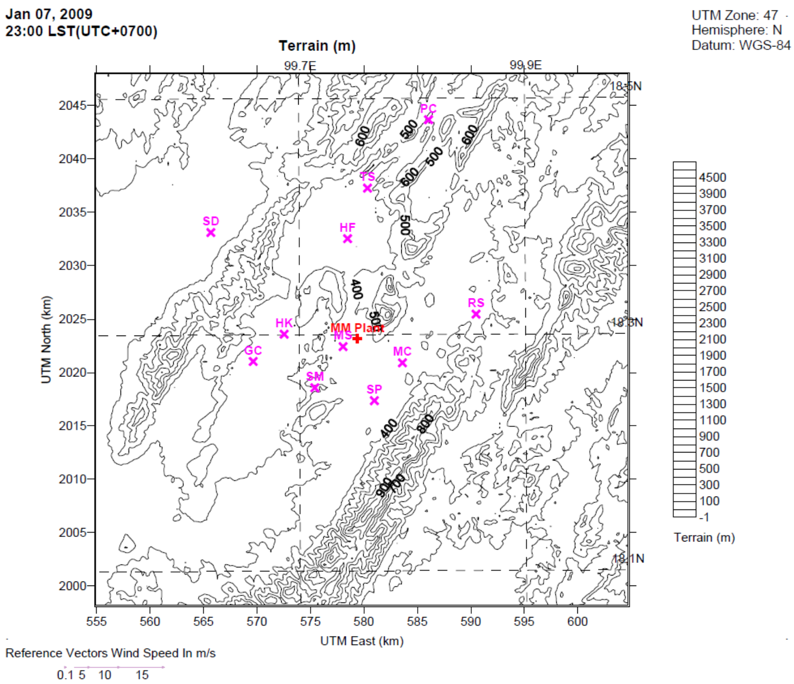

Figure 1. Terrain and locations of monitoring stations in the modeling domain

2.2 Source Characteristic

The emission source for this study is from Mae Moh power plant, the largest fossil fuel power plant in northern Thailand. This plant has 10 boilers with total capacity of 2400 MW. There are eight stacks at the plant. Details are shown in Table 2.

Table 2. Stack characteristics of the Mae Moh power plant

	MW.	Stack height (m)	Stack diameter(m)	Stack gas temperature (K)	Stack gas exit velocity(m/s)
Unit 1-3	-	-	-	-	-
Unit 4-5	300	155	5.90	377	20
Unit 6-7	300	155	5.90	381	25
Unit 8	300	150	5.75	362	20
Unit 9	300	150	5.75	361	18
Unit 10	300	150	5.75	363	21
Unit 11	300	150	5.75	363	20
Unit 12	300	155	5.90	353	16
Unit 13	300	155	5.90	351	18

2.3 Emission Monitoring Stations

Each monitoring station contains multiple gaseous pollutant analyzers for SO_2, NO_2, PM10, TSP, CO, and O_3 measurement. Concentration data from these monitoring stations are available online, and can be accessed in real time to the power plant supervisory team. Under the circumstances where SO_2 concentration has tendency to exceed the alarming level, the team might consider shutting down some power generators as a countermeasure to prevent excessive atmospheric level of SO_2.

Meteorological measurements are also routinely undertaken at the monitoring stations. These measurements include wind speed, wind direction (Figure 2), ambient temperature, surface pressure and relative humidity (Table 3). In this study, these meteorological data were used as input to CALMET model, and SO_2 concentrations were used for comparison with the model simulation results. Simulation was performed for 1-31 January, 1-31March and 1-31 October 2009, totaling 63 days.

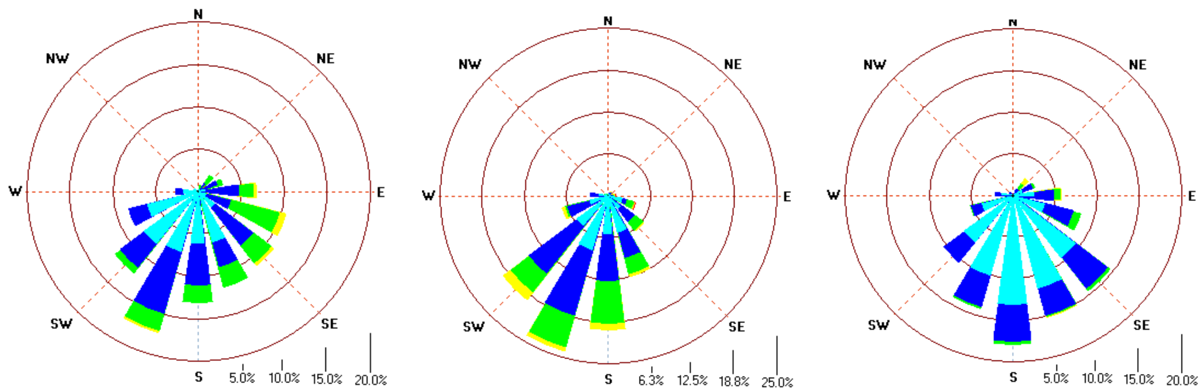

Figure 2. WindRose of January, March and October 2009

Table 3. Parameter of ambient temperature, surface pressure and relative humidity

Parameter	January 2009	March 2009	October 2009
Ambient temperature (degree of Celsius)	8.76-32.36	17.22-37.86	20.24-33.17
Surface pressure (mbar)	969-986	962-977	965-977
Relative humidity (%)	27-98	13-97	45-100

2.4 Meteorological Modeling

From the power plant previous experience in 2009, high concentrations of SO_2 were observed to occur in January, March and October for winter, summer and rainy seasons, respectively. The concentrations were the highest, among data recorded during the past five years. These months were therefore chosen as representatives for this simulation study. The days used were those with the highest emissions monitored.

CALMET meteorological model was employed for this study because it is designed to produce hourly fields of three-dimensional winds and various micrometeorological variables based on the input of routinely available surface and upper air meteorological observations. The model requires geophysical data including gridded fields of terrain elevations and land use categories (defining surface roughness, albedo, Bowen ratio, etc.). In this case, the gridded geophysical data, including land use category and terrain height were generated from USGS terrain and land use database. Meteorological data for January, March and October 2009 from the 11 monitoring stations and data set from the meso-scale meteorological model (MM5) were used as input to the model to generate the diagnostic meteorological field. The 11 vertical layers were set at heights of 20, 40, 80, 140, 240, 420, 700, 1100, 1700, 2500 and 3600 m.

2.5 SO_2 Dispersion Modeling

CALPUFF was used in this study to simulate long-range transport of SO_2 in the atmosphere. The CALPUFF modeling system includes three main components: CALMET, CALPUFF, and post processing and graphical display programs (EPA, 1998). In this work, the modeling was performed to simulate SO_2 dispersion in three season episodes. The modeling results were then compared with the measurement data.

2.6 Statistical Data Analysis

Application of various statistical parameters was undertaken and discussed by Elbir (2003) in comparison between predicted and observed data sets. Similar evaluation was carried out in this work to evaluate the performance of our model. The following parameters were calculated; root mean squared error (RMSE) and its components (systematic and unsystematic RMSE), correlation coefficient, and index of agreement. They are defined as:

Index of agreement (d)

$$d = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(|P_i - O| + |O_i - O|)^2}, \qquad (1)$$

Correlation coefficient (r)

$$r = \left[\frac{\sum_{i=1}^{N}(O_i - O)(P_i - P)}{\sigma_O \sigma_P} \right], \tag{2}$$

Systematic RMSE

$$\mathrm{RMSE_S} = \left(\frac{1}{N} \sum_{i=1}^{N} (\hat{P}_i - O_i)^2 \right)^{1/2}, \tag{3}$$

Unsystematic RMSE

$$\mathrm{RMSE_U} = \left(\frac{1}{N} \sum_{i=1}^{N} (\hat{P}_i - P_i)^2 \right)^{1/2}. \tag{4}$$

Total RMSE

$$\text{Total RMSE}^2 = \mathrm{RMSE_S^2} + \mathrm{RMSE_U^2}. \tag{5}$$

where N is the number of data, P_i is the model prediction value, O_i is the observed concentration, and O is the mean value of the observed data. σ_O and σ_P are standard deviations of the observed and predicted data. $\hat{P}_i$ is derived from the least square regression of P_i and O_i, respectively.

3. Results and Discussion

3.1 Meteorological Patterns

Typical wind vectors over the study area in a representative winter day (7 January 2009) were presented in Figure 3. It can be seen that the wind came from the north-eastern direction. Analysis of all grids in the domain by CALMET modeling revealed that in the early morning at 06:00, wind speed at 110 m level was in the range between 0.01 – 14.06 m/s, and mixing height was 50 – 1097 m, while at Mae Moh power plant, mixing height was 50 m, just under stack exit. At noon, wind speed at 110 m was 0.01 – 3.59 m/s, and mixing height was 50 - 1759 m, meanwhile at the power plant, mixing height was about 300 m. Because of low wind speeds and relatively small mixing heights over stack, accumulation of SO_2 could potentially occur as air dispersion was rather limited by stable atmospheric condition. Meteorological conditions in the evening (18:00 and 23:00) were similar to those in the early morning at 06:00.

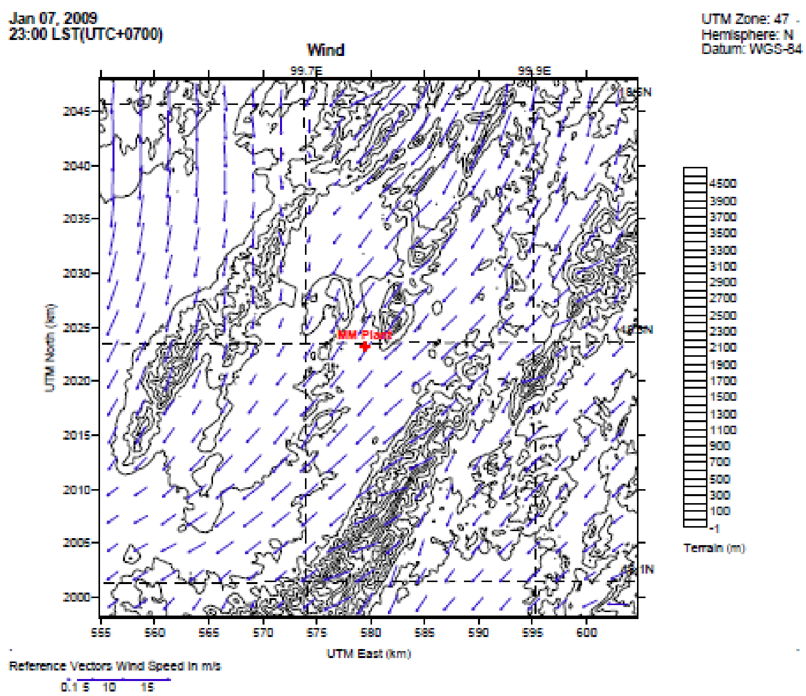

Figure 3. Typical wind vector on a representative winter day

3.2 SO_2 Spatial Distribution

Dispersion of SO_2 was mainly dependent upon wind direction and strength. It was found that in the early morning (06:00) and late evening (23:00), there were large air movements from north-eastern direction. The mixing height was only 50 m, just below the stack outlet. Under this circumstance, accumulation of SO_2 was unlikely to occur. Therefore, the concentrations were very low at both times. At midday, the wind speed blowing over the domain was found to be very low and the mixing height was slightly higher than the plant stack height. Under these conditions, capping of gaseous plume could occur, preventing the SO_2 dispersion to the upper atmosphere. Figure 4 shows the predicted spatial distribution of SO_2 at 12:00 on a representative winter day. High concentrations of SO_2 were found in the downwind areas close to the power plants. Figure 5 shows the comparison between the model results and monitoring data from all stations at the same time of day. The predicted SO_2 concentrations were found to agree well with the measurement, with standard deviation of 8.16 µg/m^3.

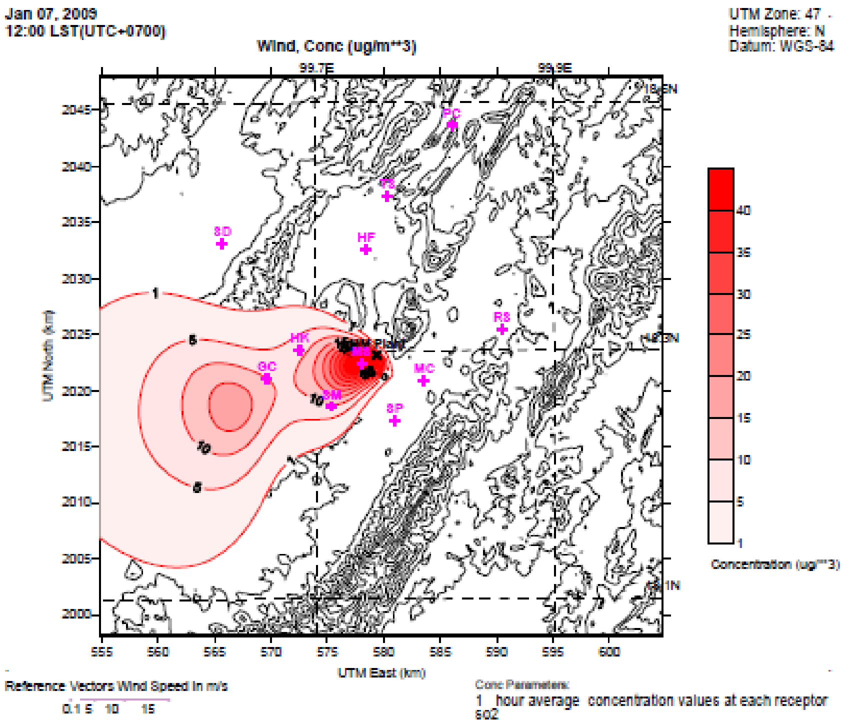

Figure 4. Predicted spatial distribution of SO_2 at noon on a representative winter day

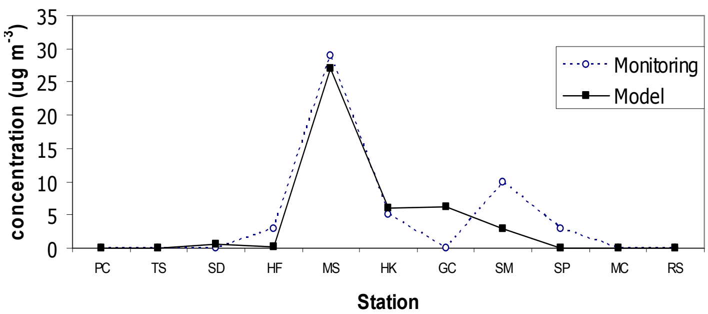

Figure 5. Comparison between measured and predicted data on a representative winter day

3.3 SO_2 Temporal Variation

Figures 6 - 8 show daily variation of SO_2 concentrations at locations of three monitoring stations; namely Ban Sop Moh, Pratupha Army Camp, and Mae Moh Government Center throughout the months of January, March and October, respectively. High concentration episodes ($\geq$ 10 µg/m^3) were evident. The predicted daily average values of the SO_2 concentrations were also found to follow similar temporal patterns to measurement values. For absolute value, simulation results appeared to slightly over-predict when compare to monitored data. Stable atmospheric stratification, calm (low wind speed), and presence of a ground-base inversion were normally encountered during winter in Mae Moh basin. These were unfavorable meteorological conditions for efficient mixing of pollutants, giving rise to possible high concentration episode.

For the case of low concentration episodes (< 10 µg/m^3), the predicted and measured daily averages of the SO_2 concentration at the three monitoring stations were compared (shown in Figures 9-11). The model appeared to show large variation in this case, especially during monsoon with rain and precipitation.

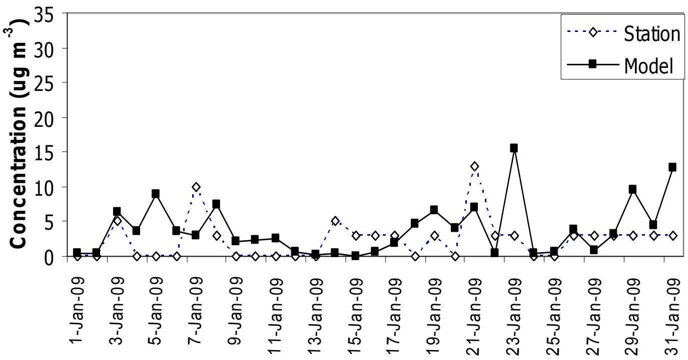

Figure 6. Comparison between measured and predicted data during high concentration episode in winter

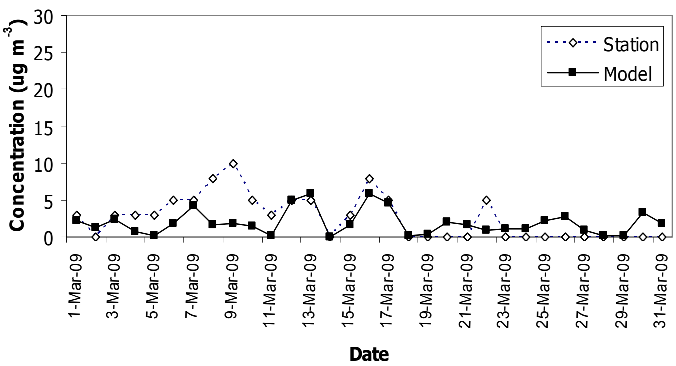

Figure 7. Comparison between measured and predicted data during high concentration episode in summer

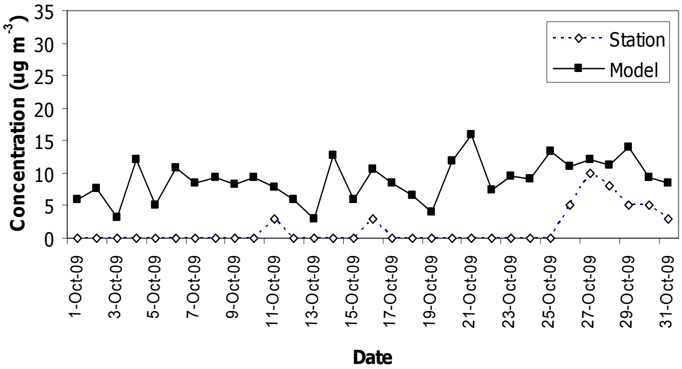

Figure 8. Comparison between measured and predicted data during high concentration episode in rainy season

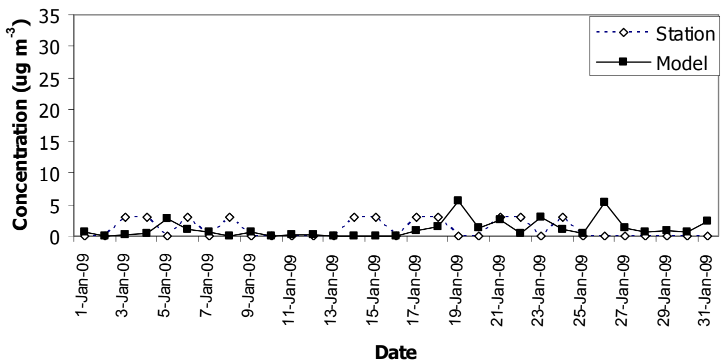

Figure 9. Comparison between measured and predicted data during low concentration episode in winter

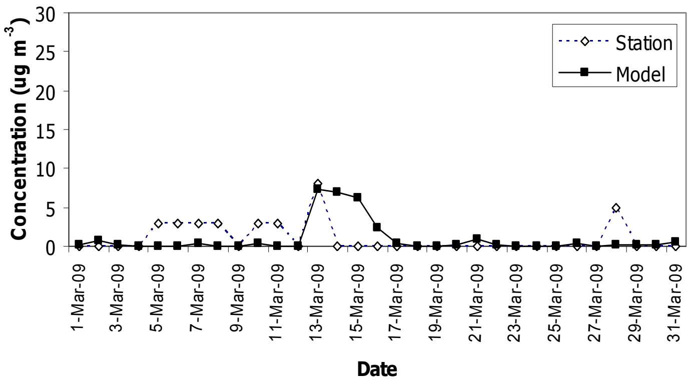

Figure 10. Comparison between measured and predicted data during low concentration episode in summer

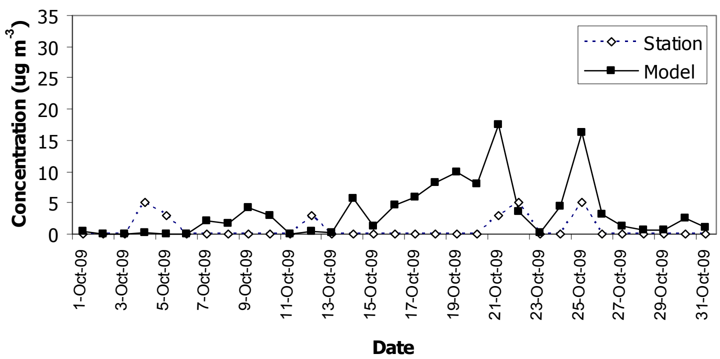

Figure 11. Comparison between measured and predicted data during low concentration episode in rainy season

3.4 Statistical Analysis

Table 4 presents the mean, maximum and standard deviation, together with other statistical parameters for the measured and predicted daily SO_2 concentrations in the year 2009. The index of agreement (*d*) was found to vary from 0.0 (theoretical minimum) to 1.0 (perfect agreement between the observed and predicted values). The value of *d* should be close to 1.0 and total RMSE should be close to 0.0 for good prediction. From this work, statistical comparison between the model results and the measured data from six monitoring stations showed moderate degrees of agreement ranging from 0.36 to 0.73. Standard errors in terms of total RMSE were found in the range between 2.19 to 8.32 μg/m^3. Analysis of RMSE indicated comparatively small systematic error, with unsystematic error approaching the RMSE. Overall, quantitative evaluation of the model results revealed that the simulated model performance was very good, especially for winter and summer seasons.

Table 4. Statistical analysis of the predicted and observed time series of SO_2 concentration

Statistical parameter	Winter				Summer				Rainny			
	Ban sa det		Ban sop moh		Government center		Pratupha army camp		Ban mae chang		Government center	
	predic	Obs.	predic	Obs.	predic	Obs.	predic	Obs.	predic	Obs.	predic	Obs.
Mean (μgm^{-3})	1	1	4	2	1	1	2	3	3	1	9	1
Max (μgm^{-3})	5	3	16	13	7	8	6	10	18	5	16	10
Standard dev. (μgm^{-3})	1	1	4	3	2	2	2	3	5	2	3	3
Number of Valid observations	31		31		31		31		31		31	
Index of agreement (d)	0.73		0.56		0.41		0.36		0.62		0.64	
Correlation coefficient ®	-0.19		0.23		0.28		0.47		0.32		0.34	
Systematic RMSE (RMSEs)	1.70		2.55		1.34		2.19		2.70		7.80	
Unsystematic RMSE (RMSEu)	1.38		3.70		1.92		1.46		4.20		2.91	
Total RMSE	2.19		4.49		2.34		2.63		5.00		8.32	

4. Conclusion

This paper presents simulation of sulfur dioxide dispersion from Mae Moh power plant, and comparison between the predicted and measured concentrations in the Mae Moh basin. Both measured and predicted data included daily SO_2 concentrations from three seasons of the year 2009. For all monitoring stations, the predicted SO_2 concentrations were found to agree qualitatively well with the measured data. Quantitatively, several overpredictions were observed, especially during rainy season. These differences might be caused by the influence of complex area from mountain terrains in Mae Moh basin, and uncertainties of measured data and meteorological data used in the model. Our findings showed that the CALPUFF model can be used for the SO_2 dispersion prediction with approximate accuracy. The model appeared to be a valuable tool in evaluating air pollutants dispersion from Mae Moh power plant to its vicinity.

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References

Bandyopadhyay, A. (2009). Prediction of ground level concentration of SO_2 using ISCST3 model in Bangalore industrial region of India. *Clean Technologies & Environmental Policy, 11*, 173-188. http://dx.doi.org/10.1007/s10098-008-0188-x

Cohen, J., Cook, R., Bailey, C. R., & Carr, E. (2005). Relationship between motor vehicle emissions of hazardous pollutants, roadway proximity, and ambient concentrations in Portland, Oregon. *Environmental Modelling & Software, 20*, 7-12. http://dx.doi.org/10.1016/j.envsoft.2004.04.002

Doolgindachbaporn, T. (1995). *CALPUFF dispersion model study of ambient SO_2 concentrations around the Mae Moh thermal power plant in Thailand.* MEng Thesis, Asian Institute of Technology, Thailand.

Elbir, T. (2003). Comparison of model predictions with the data of an urban air quality monitoring network in Izmir, Turkey. *Atmospheric Environment, 37*, 2149-2157. http://dx.doi.org/10.1016/S1352-2310(03)00089-6

Environmental Protection Agency. (1998). Interagency workgroup on air quality modeling phase 2 summary report and recommendations for modeling long range transport impacts. Retrieved April 3, 2011, from http://www.epa.gov/ttn/scram/7thconf/calpuff/ phase2.pdf

Jiang, G., Lamb, B., & Westberg, H. (2003). Using back trajectories and process analysis to investigate photochemical ozone production in the Puget Sound region. *Atmospheric Environment, 37*, 1489-1502. http://dx.doi.org/10.1016/S1352-2310(02)01027-0

Jirungnimitsakul, S., & Kreasuwan J. (2004). Application of CALPUFF model on sulfur dioxide dispersion from Mae Moh power plant*, 30th Congress on Science and Technology of Thailand*, 19-21 October, Bangkok, Thailand.

Jitman, B. (2010). *Mae Moh power plant lignite coal handing management*. Retrieved January 7, 2012, from http://www.aesieap0910.org/upload/File/ PDF/4-Technical%20Sessions/TS28/TS2804/TS2804%20FP.pdf

Jonathan, L., & Lovell, C. A. K. (1998). *Weather and pollution abatement costs*. Retrieved December 15, 2011, from http://www.allbusiness.com/government/environmental-regulations/680525-1.html

Kanokkanjana, K. (2004). *Modeling tool for air quality management of the Laem Chabang industrial estate.* MEng Thesis, Asian Institute of Tecnology, Thailand.

Levy, J. I., Spengler, J. D., Hlinka, D., Sullivan, D., & Moon, D. (2002). Using CALPUFF to evaluate the impacts of power plant emissions in Illinois: Model sensitivity and implications. *Atmospheric Environment,* *36*, 1063-1075.

Patima, P. (2006). *Analysis of sulfur dioxide dispersion in Laem Chabang industrial complex by CALPUFF model.* MSc Thesis, Chiang Mai University, Thailand.

Scire, J. S., Strimaitis, D. G., & Yamartino, R. J. (2000). *A user's guide for the CALPUFF dispersion model*. Retrieved February 20, 2012, from http://www.src.com/calpuff/calpuff1.htm

Tuaycharoen, P., Wongwises, P., Aram, R. P., & Satayopas, B. (2008). Nitrogen oxide (NOx) dispersion model for Khanom power plant area. *International Conference on Environmental Research and Technology,* Penang, Malaysia.

Varna, M. G., & Gimsom, N. R. (2002). Dispersion modeling of a wintertime particulate pollution episode in Christchurch, New Zealand. *Atmospheric Environment, 36*, 3531-3544.