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Air Pollution Dispersion Modelling using GRAL in Area Near Coal-Steam Power Plant at Central Java

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ABSTRACT

Sulfur dioxide and Nitrogen dioxide were significant emissions emitted from coal-steam power plants that may cause health problems for humans and damage the environment. Studying the SO_2 and NO_2 gradients in Indonesian residential communities is critical for evaluating resident's SO_2 and NO_2 exposure. The method developed to assist analysis of spatial SO_2 and NO_2 gradients on a community scale combines a mesoscale Lagrangian dispersion model with field observations around coal-steam power plants using GRAL. The objectives of this study focused on GRAL dispersion of SO_2 and NO_2 in an Indonesian residential community near the coal-steam power plant, with a 6 km x 8 km resolution. Analysis of this model indicates a correlation between simulation and observation, with SO_2 coefficient correlation (R) within 0.5 – 0.82 and NO_2 coefficient correlation (R) within 0.30 – 0.59. Model performances analyze by NMSE and FB. The SO_2 model is comparable to observation data since it has a better average NMSE and FB than the NO_2 model. Due to data limitation of observation collected by grab sampling instead of continuous ambient measurement system affect different respond time compared with hourly data from the model.

1. INTRODUCTION

Sulfur Oxides, mainly Sulfur Dioxide (SO_2), emitted by coal-steam power plants may cause health impacts for humans with increased cardiovascular disease risk in long term exposures (Fatkhurrahman et al., 2020; Lin et al., 2018). Short-term exposures can make breathing difficult for people with asthma (Galán, Tobías, Banegas, & Aránguez, 2003). It also degrades the climate by producing acid rain in the environment (Jain, Cui, & Domen, 2016). The coal-steam power plant also releases massive Nitrogen Oxide as Nitrogen Dioxide (NO_2) into the atmosphere; the photochemical reaction may produce atmospheric ozone, which is harmful for lung function and other respiratory problems (Zhang, Wei, & Fang, 2019). In Indonesia, twenty coal-steam power plants utilize electricity generation, primarily built in Java, close together to dense housing.

In comparison, more than ten coal-steam power plants are planned for construction in future years (Quina, Fadhillah, Jiaqiao, & Zhao, 2017). Mainly, coal-steam power plants conduct emission tests using external testing laboratories; they could also install a continuous emission monitoring system (Simbolon et al., 2021). Therefore, studying the SO_2 and NO_2 gradients in Indonesian residential communities is critical for evaluating resident's SO_2 and NO_2 exposure. In Indonesia, there are several problems to conduct a comprehensive analysis of SO_2 and NO_2 exposure in the environment. The complexity of the emissions and building arrangements spreads in large areas.

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The lack of meteorological data available for the public makes the air pollution study take a difficult step.

Indonesian coal-steam power plants commonly built near the coast may cause air pollution dispersion through the coastal climate into the residents near the beach. It will be affected dominantly by sea windblown into the land, dispersing SO_2 and NO_2 from coal-steam power plants chimney for the entire year. As two significant seasons in Indonesia, the rainy and dry seasons, more pollution in the dry season will be possible than in the rainy season. The method was developed to assist in analyzing spatial SO_2 and NO_2 gradients on a community scale that combines a mesoscale Lagrangian dispersion model with field observations around coal-steam power plants. Popular air quality models like WRF-Chem and AERMOD can be utilized on regional to urban scales (Grell et al., 2005; Mijling, 2020). AERMOD is a paid software with more than USD 1000 cost to buy, while WRF-Chem is free software but needs advanced programming language knowledge. This study employs the Graz Lagrangian (GRAL) model for SO_2 and NO_2 simulation (Oettl, 2014; Romanov, 2020). GRAL can be applied for gaseous and particulates simulation and prediction for flat and complex terrain, mainly based on daily, monthly, and annual means (Anfossi et al., 2006). This GRAL system is entirely free, and study using GRAL seems to be applied both for urban scale, areas near industries, and even some tight tunnel openings (Ling, Candice Lung, & Uhrner, 2020). GRAL system is commonly prevalent in Europe, based on published validation studies by annual means (Kurz et al., 2014). There is also a GRAL limitation on chemical reaction modeling in the atmosphere that should be noticed when air dispersion simulation conduct in the area with chemical reaction happened. However, GRAL has not yet been validated in an Asian residential community, especially for Indonesian typical residential and population arrangement. In this study, SO_2 and NO_2 monitoring are compared with simulations at the residential level side by side with grab sampling of ambient measurement and evaluated as an hourly means. This study's novelty is Lagrangian mesoscale modeling to study SO_2 and NO_2 dispersion in typical Indonesian residential communities, which is free software, easy to operate with the large capacity of modeling computation with friendly GUI run in a familiar operating system like Windows. The main objectives were; to validate GRAL comprehensively on SO_2 and NO_2 dispersion in an Indonesian residential community near the coal-steam power plant, with a 6 km x 8 km resolution, and evaluate three-dimensional dispersion of coal-steam power plant SO_2 and NO_2 in areas near to it, with 48 square kilometres domain.

2. METHOD

2.1 Site description and observations

The community in this study was a typical Indonesian residential community near the coal-steam power plant in southern Java. Based on topographical characteristics, the residential community's mean building height was 3 meters. This coal-steam power plant has two-unit processes, with has a stack height of 240 meters and 220 meters, with 6.8-meters and 7.8-meters inside diameters. Based on this data, there is a possibility to simulate monthly SO_2 and NO_2 as dominant emissions from the coal-steam power plant. Simulation using GRAL was analyzed in quarterly periods as the ambient measurement was conducted every three months. Each parameter will be analyzed respectively. NO_2 concentration will convert from NO_x as empirical equation (1) (Middleton, Luhana, Sokhi, & Great Britain. Environment Agency., 2007), where NO_2 concentration would be equal as 1.58 times with NO_x order to 0.6887 as constant.

$$NO_2 = 1{,}58 \times {NO_x}^{0.6887} \quad (1)$$

SO_2 and NO_2 in ambient air measured in eleven points, within hundreds of meters to several kilometers from the coal-steam power plant, SO_2 measured by pararosaniline method on an hourly basis, while NO_2 measured by Griesz

Saltzman method also on one hourly. Intercomparison analysis for each receptor was evaluated using the statistical method.

2.2 Modeling approach

This study's GRAL model (v20.09) simulates the dispersion of multi-source gases and particulates using synoptic meteorological data. However, based on the typical topography of southern Java, where this coal-steam power plant is located, any obstacles were assumed to be ignored since there was typically flat terrain around the model domain region. Schematic for GRAL model as seen in figure 1 below.

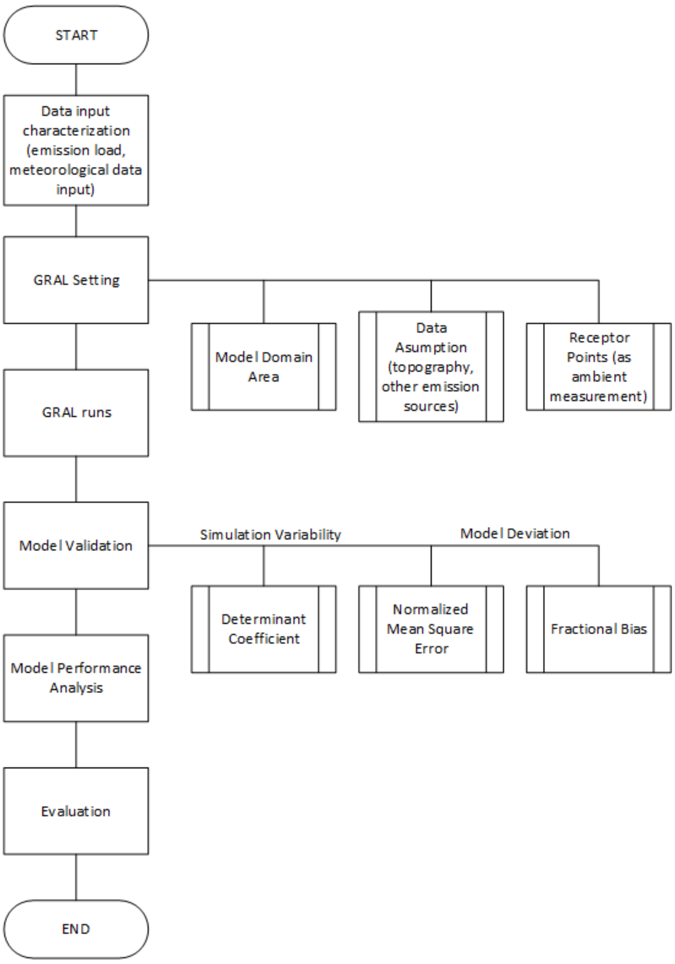

Figure 1. Schematic Run of GRAL Model

Most Gaussian dispersion models can be used for flat terrain simulation, such as CALINE 4 (Dhyani, Singh, Sharma, & Gulia, 2013), AERMOD, ADMS (Carruthers et al., 2011), and OSPM (Hu & Zhong, 2010). GRAL system can simulate dispersion for both flat terrain and complex terrain (Oettl, 2015). GRAL was efficient to its CPU time and minimum disk space computing requirements and can be used across microscales to mesoscales (Berchet et al., 2017). Meteorological wind data was collected using Copernicus ERA 5 Climate Reanalysis (Oses et al., 2020). Data was collected for the whole year in 2018 within hourly intervals, both for wind speed and wind direction meteorological data input. Data was collected through the model domain for 6 km x 8 km. As this research focused on the housing height from the ground, the vertical height was set to a minimum of 3 meters.

2.3 Model limitation, validation, and evaluation

The simulation result is initially outputted as the SO_2 and NO_2 concentration field from each emission source. At the receptor point, the total SO_2 and NO_2 concentration (C_{total}) was calculated using this equation (2);

$$C_{total} = C_{blank} + C_1 + C_2 \qquad (2)$$

C_{blank} as background concentration for SO_2 is 13.5 µg/Nm^3 based on (Rogers et al., 1999) and NO_2 are 14.8 µg/Nm^3 based on (Jarvis, Adamkiewicz, Heroux, Rapp, & Kelly, 2010) both are atmospheric concentration trend similar in large Indonesia cities (Susanto, 2005). C_1 and C_2 are the specific SO_2 and NO_2 increments related to each SO_2 and NO_x emission source. Here C_1 and C_2 were SO_2 and NO_x emissions from each coal-steam power plant stack chimney. Normalized mean square error (NMSE) and fractional bias (FB) were used to determine the optimum parameters and assess the model performance (Ling et al., 2020). This assessment can be calculated using equations (2) and (3).

$$NMSE = \frac{(C_{obs}-C_s)}{C_{obs}\times C_s}; \text{ (ideal value 0, accepted value} \leq 4) \qquad (2)$$

$$FB = \frac{C_{obs}-C_s}{0{,}5\times(C_{obs}+C_s)}; \text{ (ideal value 0, accepted value } -0{,}3 \leq FB \leq 0{,}3) \qquad (3)$$

C_{obs} are observed SO_2, and NO_2 concentration and C_s are simulated SO_2 and NO_2 concentration as hourly means, respectively.

3. RESULT AND DISCUSSION

3.1 Characteristics of the Area and Emission

Studying the dispersion of SO2 and NO2 near the coal-steam power plant in southern Java can evaluate over the near region around the coal-steam power plant. This coal-steam power plant is located in coastal south Java, verge with Hindian ocean in the south. Around the coal-steam power plant, there is another coal-steam power plant 8 km to the east. Emission source data for this coal-steam power plant does not include in this study. There are two major emission sources at the western side of the coal-steam power plant: cement industries and oil and gas refinery plants within the 8 km range.

This coal-steam power plant has two chimneys; chimneys 1&2 are one chimney from two separate processes, and chimney 3 emits dominant SO_2 and NOx to the atmosphere. Each quarter, an external laboratory conducts emission monitoring and emission load, as seen in table 1. Ministry of Environment Regulation No. 21 the year 2008 stated there is no emission load limit while emission rate should follow that regulation strictly.

Figure 2. Geographical Characteristics Around Coal-steam Power Plant

Table 1. Emission load from coal-steam power plant

No	*Parameter*	*Chimney 1&2*				*Chimney 3*				Value
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
1	SO2	2941	605.4	201.8	634.8	2536.8	545.5	28.2	209.6	kg/h
2	NOx	943.3	2224	1964.4	864.3	428	1865.7	455.1	688.4	kg/h
3	Q	1175	1509.8	1175.7	1183.3	1199.8	1867.1	1216.1	940.8	m^3/s

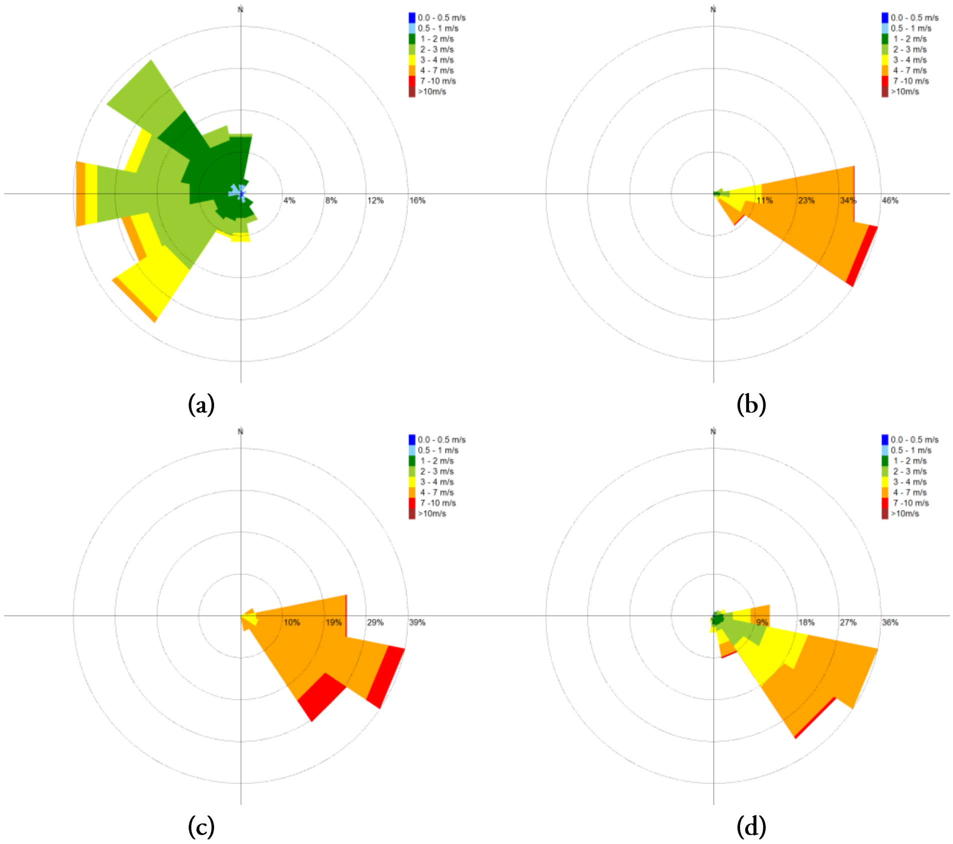

Figure 3. Spatial wind direction dominant around coal-steam power plant ; (a) 1st quarter, (b) 2nd quarter, (c) 3rd quarter, (d) 4th quarter

Around the coal-steam power plant, ten receptor points are measured manually for SO_2 and NO_2 quarterly based on the AMDAL document, similar to emission data from the coal-steam power plant.

There were twenty-one receptors for ambient measurement around it, but only ten-point measures of SO_2 and NO_2, in figure 2, are signed by A4, A6, A8, A10, A11, A12, A15 A16, A17, and A18. Evaluating this potential dispersion pollutant possibility from the coal-steam power plant to the receptor point needs meteorological data in a quarterly period. Meteorological data from Copernicus ERA 5, wind speed, and wind direction data were collected hourly for 2018 data. Both wind speed and wind direction data around coal-steam power plant as seen in figure 3.

Annual average of wind direction based on figure 3 wind rose originally come from South-East. The pollutant dispersion tends to disperse to the land at the Westside to the Northside of the coal-steam power plant. By quarterly analysis, only 1st quarter tends dispersion will happen from the West side of the coal-steam power plant to the Eastside. While wind speed distribution in figure 3 indicates an average annual wind speed as high as 3 – 6 meters per second. Wind speed indicates how pollutants will be diluted over the dispersion period (Kim, Lee, Woo, & Bae, 2015). The concentration contour of SO_2 and NO_2 for each quarter can be seen in Figure S1-S8.

3.2 Intercomparison Model to Observation

SO_2 and NO_2 concentration from GRAL simulation for each receptor point was analyzed by intercomparison using ambient measurement in ten receptor points. This ambient data was collected by grab sampling method using the pararosaniline method for SO_2, and Griesz Saltzmann method for NO_2 the data compared as seen in Figure 4 and figure 5.

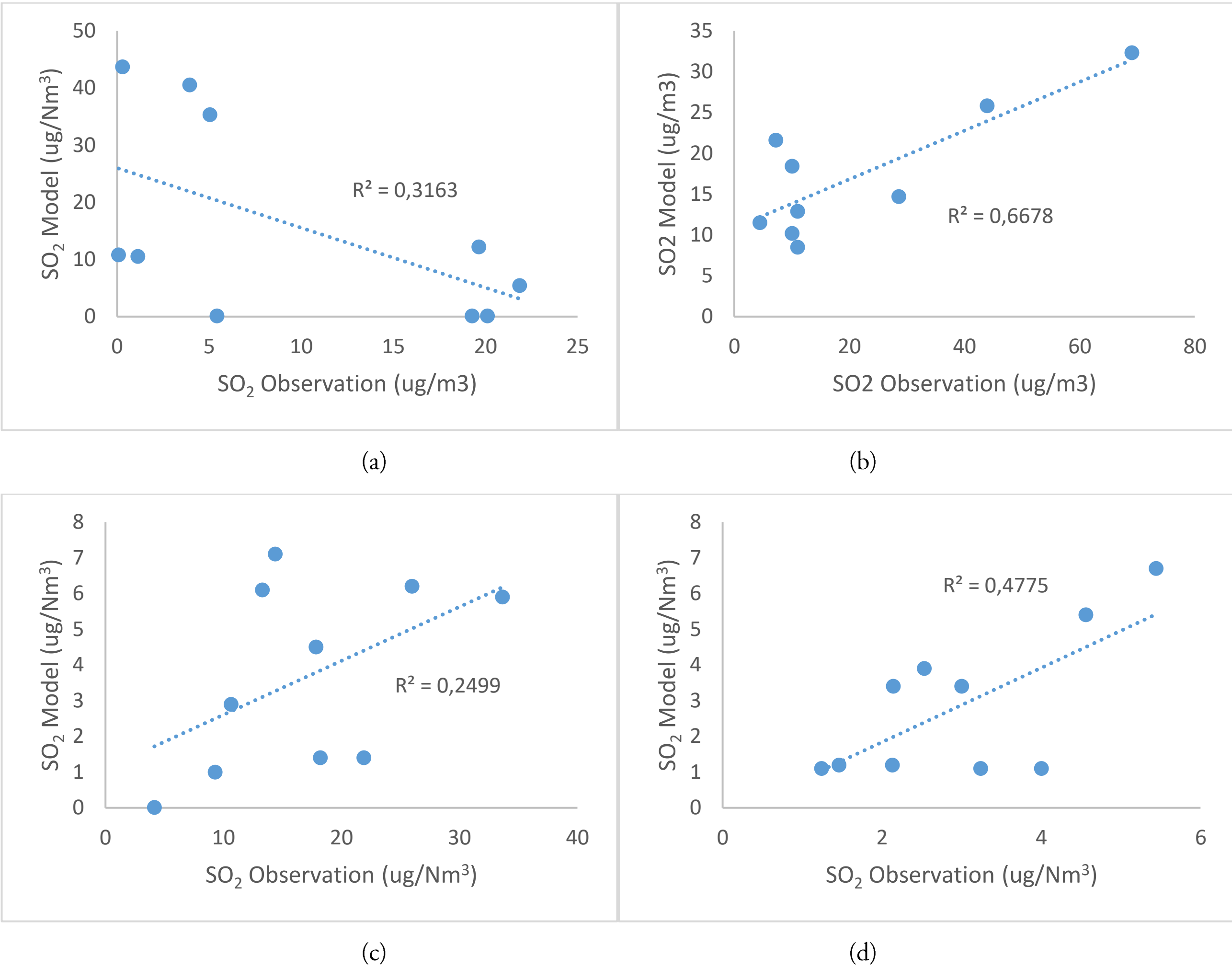

Figure 4. Scatter plot showing the relationship between SO_2 observation and model; (a) 1st quarter, (b) 2nd quarter, (c) 3rd quarter, (d) 4th quarter

Observation data and modeled data relationships are shown by coefficient correlation (R). Based on simulation and observation data, there is a coefficient correlation within the range of 0.5 – 0.82, which is good enough for modeled-based air pollution dispersion since it compared grab sampling and hourly modeled data. At Q1, based on the wind rose in figure 3, dominant dispersion happened from the west to the east that caused no dispersion of the pollutant from the coal-steam power plant to the receptor in the west side (A12, A10, A18, A16, A15, A6, A11, and A4). A receptor (A8) is located far to the north side to get minimum pollutant dispersion from the coal-steam power plant. This concentration is relatively equal to ambient measurement, shown below the detection limit of the pararosaniline method. In Q3 and Q4, wind direction dominantly came from the south-east and east sides; this result underestimates simulation results compared to observation data.

NO_2 variability in figure 6 is shown as coefficient correlation. It has a range between 0.30 – 0.59. Q3 and Q4 shown the best linear correlation between simulation and observation data. These phenomena could happen because the domestic combustion process and transportation can produce NO_2. At receptor points A6, A6, A8, and 18, where measurement site near the public street, NO_2 observation data shown higher than simulation data. Deviation of the simulation as model performance analysis by NMSE and FB (Chang and Hanna, 2004), NMSE, and FB value for SO_2 and NO_2 are seen in table 2 and table 3.

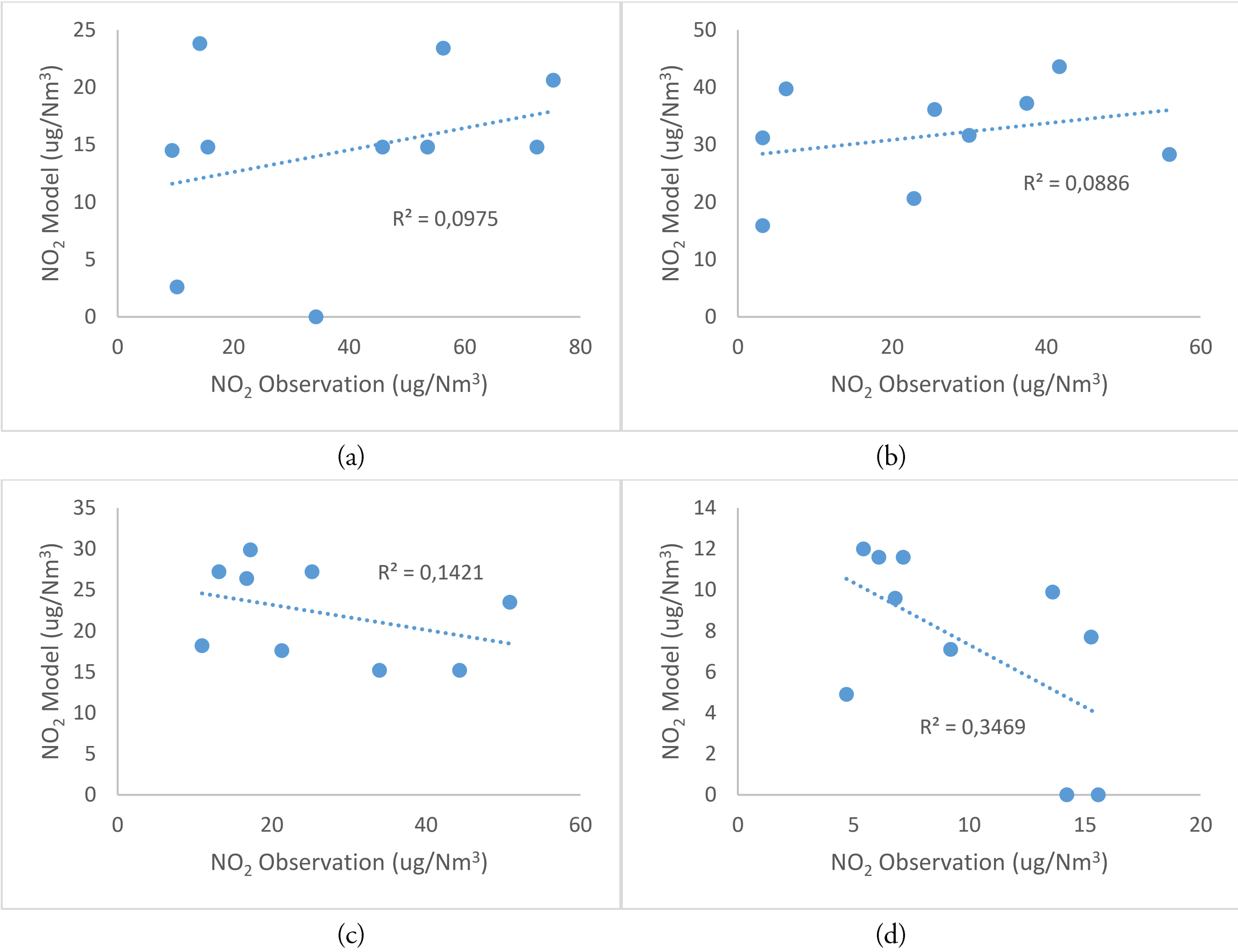

Figure 6. Scatter plot showing the relationship between NO_2 observation and model; (a) 1st quarter, (b) 2nd quarter, (c) 3rd quarter, (d) 4th quarter

Table 2. NMSE and FB for SO_2 for each location and quarter

NO	*Location*	*Q1*		*Q2*		*Q3*		*Q4*	
		NMSE	FB	NMSE	FB	NMSE	FB	NMSE	FB
1	A4	0.139	1.208	-0.002	-0.020	0.669	1.760	0.364	0.559
2	A6	9.950	1.980	0.027	0.256	0.659	1.714	0.600	0.986
3	A8	0.031	0.468	-0.013	-0.159	0.166	1.194	-0.173	-0.455
4	A10	9.815	1.928	0.016	0.520	0.140	1.403	-0.139	-0.426
5	A11	9.948	1.979	0.033	0.641	0.892	1.612	0.148	0.195
6	A12	-0.229	-1.645	0.016	0.725	0.071	0.678	-0.035	-0.208
7	A15	-12.728	-1.971	-0.139	-0.887	0.251	1.143	0.103	0.120
8	A16	-0.795	-1.614	-0.045	-0.587	0.089	0.742	-0.039	-0.125
9	A17	-3.299	-1.973	below detection limit		99.758	1.990	0.659	1.137
10	A18	-0.170	-1.500	-0.093	-1.001	0.123	1.229	-0.034	-0.169
	Average	1.266	-0.114	-0.022	-0.057	10.282*	1.347*	0.145	0.161

Table 3. NMSE and FB for NO_2 for each location and quarter

NO	*Location*	*Q1*		*Q2*		*Q3*		*Q4*	
		NMSE	FB	NMSE	FB	NMSE	FB	NMSE	FB
1	A4	0.035	1.141	0.005	0.102	0.010	0.190	0.032	0.257
2	A6	0.054	1.322	0.017	0.656	0.043	0.979	99.930	1.997
3	A8	0.025	0.825	0.0002	0.007	0.023	0.736	-0.043	-0.342
4	A10	0.003	0.051	-0.001	-0.045	-0.025	-0.538	-0.101	-0.754
5	A11	0.046	1.023	-0.250	-1.330	0.036	0.763	-0.009	-0.043
6	A12	0.049	1.135	-0.012	-0.345	-0.003	-0.076	-0.078	-0.622
7	A15	-0.028	-0.504	-0.280	-1.628	-0.037	-0.499	0.064	0.659
8	A16	99.971	1.999	-0.002	-0.053	-0.039	-0.697	0.027	0.315
9	A17	-0.037	-0.425	below detection limit		below detection limit		99.936	1.997
10	A18	0.287	1.193	-0.135	-1.457	-0.022	-0.450	-0.054	-0.477
	Average	10.040*	0.776	-0.073	-0.455	-0.001	0.045	19.970*	0.299

*) : Unaccepted NMSE and FB range

Model performance by NMSE and FB indicate that the SO2 model is better than the NO2 model as the average range of NMSE and FB for SO2 qualified in accepted NMSE and FB interval. It can be concluded that the SO2 model is more comparable to observation data than the NO2 model (Bhat, Kumar, & Czajkowski, 2011; El-Fadel, Abi-Esber, & El-Fadel, 2012). The NO2 model is slightly incomparable to the observation data. It can happen due to the origin of the NO2 produced by internal combustion processes like domestic and transportation which did not include an emission source in this model. Eastern side coal-steam power industries, cement industry, and oil and gas refinery within eight kilometers range were dominant NO2 emitters which the data does not include in this study. As model input, both SO2 and NO2 were simulated using GRAL based on emission load, wind speed, and wind direction.

4. CONCLUSION

GRAL study as air pollution model near the coal-steam power plant showed a medium correlation between simulation and observation, with SO_2 coefficient correlation (R) within 0.5 – 0.82 and NO_2 coefficient correlation (R) within 0.30 – 0.59. Model performances analyze by NMSE and FB, SO_2 model seems to be more comparable to observation data since has better average NMSE and FB than NO_2 model. NO_2 emissions may be produced from the domestic and transportation process, and several industries within the region did not include an emission source in this study. Due to data limitation of observation collected by grab sampling instead of continuous ambient measurement system affects different response times compared with hourly data from the model. A comprehensive study needs to be conducted to alter this limitation. Serial observation ambient data is a must to analyze comparison between simulation and observation data on an hourly basis.

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