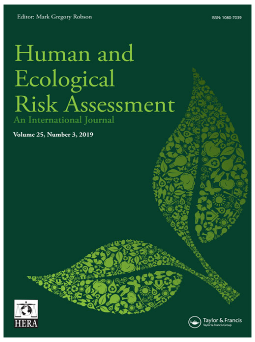

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Performance of AERMOD and CALPUFF models on SO_2 and NO_2 emissions for future health risk assessment in Tema Metropolis

Patrick Amoatey[a], Hamid Omidvarborna[b], Hannah A. Affum[c], and Mahad Baawain[b]

[a]Department of Biology, College of Science, Sultan Qaboos University, Muscat, Oman; [b]Department of Civil and Architectural Engineering, Sultan Qaboos University, Muscat, Oman; [c]Department of Nuclear Sciences and Applications, University of Ghana, Accra, Ghana

ABSTRACT

AERMOD results were compared with the reported CALPUFF results to estimate the concentrations and temporal distributions of SO_2 and NO_2 from Tema Oil Refinery with particlar attention to heavy rainy season (HRS), minor rainy season (MRS), and dry season (DS). Statistical indices, including the fractional bias (FB), geometric mean variance (VG), normalized mean square error (NMSE), index of agreement (IOA), and geometric mean bias (MG), were used to assess the reliability of the models. Overall, AERMOD better predicted ambient SO_2 and NO_2 levels than the reported CALPUFF model. For SO_2, AERMOD showed a good agreement with FB, IOA, and MG while CALPUFF showed a good prediction in NMSE and VG. Also, AERMOD predicted NO_2 well with NMSE, IOA, MG, and VG compared with FB for CALPUFF. The MRS results showed higher hourly maximum concentrations (107.4 $\mu g/m^3$ for SO_2 and 31.7 $\mu g/m^3$ for NO_2). Maximum daily concentrations were slightly higher in HRS (37.7 $\mu g/m^3$ for SO_2 and 9.6 $\mu g/m^3$ for NO_2) compared to MRS and DS. The performace of the models may provide a better understanding for future epidemiological studies.

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Air Pollutant; AERMOD; CALPUFF; Tema Oil Refinery; Ghana

1. Introduction

Air pollution is one of the serious health problems in most developing countries undergoing industrialization (Kanada *et al.* 2013); because, air pollution has received less attention as governments in these countries are focusing more on infrastructure, education, and food security. Even in cities with high-energy production and consumption, there has been little effort in monitoring and regulating ambient air quality levels (Arku *et al.* 2008; Li *et al.* 2015). Combustion of fossil fuels are the main sources of ambient air pollution as they release mainly sulfur dioxide (SO_2), oxides of nitrogen (NOx), carbon monoxide (CO), and particulate matters (PMs) to the environment (Lee and Zhou 2015; Nam *et al.* 2013; Omidvarborna *et al.* 2015a; Streeter 2016). Specifically, SO_2 and NOx are mainly released from oil refineries, power generation, biomass combustion, and various factories (Omidvarborna *et al.* 2015b; Shi *et al.* 2014; UNEP 2016). SO_2 and NOx could cause respiratory disorders such as asthma in children and

CONTACT Mahad Baawain msab@squ.edu.om Department of Civil & Architectural Engineering, Sultan Qaboos University, P.O. Box 33, Al Khould, P.C 123, Muscat, Oman.

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the aged group and predispose the public to the incidence of cancer, stroke, and cardiovascular diseases (WHO 2016). Additionally, SO_2 could form particulates of aerodynamic diameters 2.5 μm and 10 μm ($PM_{2.5}$ and PM_{10}) and may contribute to bronchitis (Amoatey *et al.* 2017; US EPA 2017). Therefore, to assess risks and threats to human health, acquiring requisite and in-depth knowledge about the levels and distribution of air pollutants in the ambient environment is imperative (Nguyen and Kim 2006).

There are several advanced air quality dispersion models including the regulatory model for long transport dispersion called California Puff Model (CALPUFF) (Affum *et al.* 2016), the US EPA Regulatory Model (AERMOD) (Seangkiatiyuth *et al.* 2011), Industrial Source Complex Model (ISCST3) (Rama Krishna *et al.* 2005), and Atmospheric Dispersion Modeling Software (ADMS) (Ali and Athar 2010). These models are developed based on the Gaussian plume model, which determines the vertical and horizontal spread of the plume, in both simple and complex terrains (Daly and Zannetti 2007). The models are being used to estimate the concentration level of different pollutants, which help to assess health risk assessment analysis. For example, Seangkiatiyuth *et al.* (2011) used AERMOD to assess the impact of NO_2 emissions from a cement plant in Bangkok, Thailand. Mokhtar *et al.* (2014) assessed the health risk effect of SO_2 from a coal-fired power plant by using AERMOD. AERMOD was employed for the prediction of hydrogen sulfide (H_2S) emissions, a neighborhood claimed issue, from a sewage treatment plant (STP) in Oman (Baawain *et al.* 2017). AERMOD predictions performed well with measured NOx and PM_{10} concentrations through the application of Weather Research Forecasting (WRF) model (Kumar *et al.* 2017). Likewise, AERMOD was used to study the line sources of SO_2 and NOx in Nova Scotia, Canada (Gibson *et al.* 2013). Although AERMOD offers an opportunity to carry out a wide array of air quality applications, Mohan *et al.* (2011) concluded that AERMOD could underpredict suspended PM (SPM) with low bias between the measured the modeling results.

CALPUFF, a nonregulatory and steady Lagrangian Puff dispersion model, is well known in simulating pollutant concentrations for long-range intervals (>50 km from the emission sources) (Daly and Zannetti 2007). Several studies have evaluated AERMOD and CALPUFF dispersion models to assess their performance with *in situ* measurements and monitoring station data for different types of atmospheric pollutants. Results from Tartakovsky *et al.* (2013) showed that AERMOD performed better than CALPUFF under robust meteorological and topographical conditions. Similarly, Rood (2014) validated both CALPUFF and AERMOD with winter tracer data and reported that at a distance of 8 km and 16 km, CALPUFF exhibited a higher correlation with tracer data than AERMOD. However, CALPUFF underpredicted the measured concentration values at the first and ninth hours compared to AERMOD. According to Thepanondh *et al.* (2016), AERMOD performed well within extreme end of ground level concentrations in the modeling domain, while CALPUFF tended to yield conservative values.

Tema is a major industrial city in Ghana, where Tema Oil Refinery (TOR), the only state-owned refinery, is located. The United Nations Environment Program (UNEP) reported that SO_2 and NOx are the major pollutants from industrial sources in Ghana. As shown in Table 1, Environmental Protection Agency (EPA) in Ghana has currently set an annual mean limit of 50 μg/m^3 and 80 μg/m^3 for SO_2 and NO_2, respectively, representing ambient air quality standards for residential areas (Ghana EPA 2017; Armah *et al.* 2010). However, the set values are relatively relaxed in comparison with other standards, and no clear and comprehensive policies from point sources have been regulated in Ghana (UNEP 2016). In

Table 1. Ambient air quality standards.

	SO_2 (μg/m^3)			NO_2 (μg/m^3)		
Standards	1 h	24 h	Annual	1 h	24 h	Annual
Ghana EPA (2010)	350	100	50	90	60	80
US EPA (2017)	212	—	—	200	—	100
WHO (2016)	—	20	—	200	—	40
EC (2016)	350	125	—	200	—	40

view of this, it is very crucial to control ambient air pollutants to assess the levels of human exposure (Vafa-Arani *et al.* 2014; Valverde *et al.* 2016; Wang *et al.* 2014).

Previous ambient air quality studies in Tema were focused mainly on PM_{10} and $PM_{2.5}$ (Amoatey *et al.* 2017; Nyarko *et al.* 2006; Ofosu *et al.* 2012; Zhou *et al.* 2013). However, limited studies on the emission of SO_2 and NO_2 have been carried out (Arku *et al.* 2008; Affum *et al.* 2016). Since TOR is one of the major sources of SO_2 and NO_2 in Tema, it is essential to systematically assess the concentration levels of such pollutants in the ambient air. Moreover, to support future health and ecosystem assessment studies within the Tema area, evaluating TOR emissions with advanced modeling systems (AERMOD and CALPUFF) will be crucial. Thus, this study seeks to predict the concentration levels of SO_2 and NO_2 in the surrounding areas of the refinery to assess the future impacts on the residents and the environment. This study will also be important in the development of local ambient air quality standards and improve human health risk assessment studies from air pollutants exposure in future.

2. Methodology

2.1. Study area

The city of Tema Metropolis is the largest industrial hub and seaport of Ghana encompassing an area of 87.8 km^2 with a population of about 292,773 in 2010 (Ghana Statistical Service 2010). The projected population of the metropolis is about 402,000 with an annual growth rate of 2.6% (Ghana Statistical Service 2010). The study area is generally characterized by high humidity, strong winds with relatively low rainfall known as Harmattan season during the months of January–March (Arku *et al.* 2008; Ofosu *et al.* 2012) and rainfall from April to November (Ghana Statistical Service 2010). The city is located 30 km to the East of Accra, the capital city of Ghana. The city lies (5°42.535′ N and 0°.111′ E) along the coastal area characterized by flat terrains with an elevation of 36 m above sea level (Figure 1). Tema metropolitan city houses around 500 light and heavy industries involved in several activities. TOR is located (5°40.172′ N and 0°.419′ E) within the industrial enclave of Tema Metropolis with a land cover of about 2–4 km radius and is surrounded by residential buildings, schools, hospitals, markets, hotels, and restaurants.

2.2. TOR emission inventory

The emission of SO_2 and NO_2 to the ambient air is due to combustion of fuels from the stacks (Table 2). In this study, the material balance procedure was used to estimate the emissions based on ideal gas laws (Affum *et al.* 2016). Stoichiometric reaction equations were

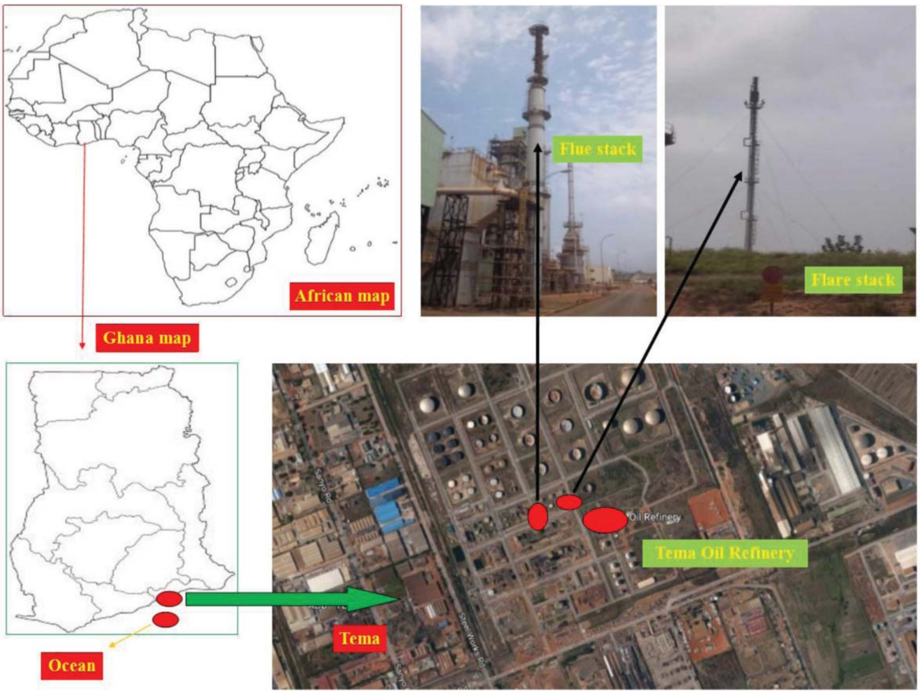

Figure 1. A map showing Ghana, TOR, and the location of stacks.

applied to account for the product concentrations based on the known concentration of the reactants (Table 3). The average data for the stacks were used as shown in Tables 2 and 4.

The annual emission rates were similar for both SO_2 and NO_2, because TOR has consistently maintained its production capacity over the years. Meteorological data for 2009 was used instead of 2008 due to the lack of data for 2008, as there may not have been significant change in weather condition within the study location for the two successive years (Affum 2015). The estimation of emission rates obtained from the material balance study is shown in Table 5. The detailed calculations of emission rates for flue gas are also shown elsewhere (Affum 2015).

2.3. Meteorological data

Both surface and upper meteorological observations were implemented for the formulation of the model. The meteorological data for 2009 was obtained from Accra International Airport (AIA) meteorological station (5°42′35.58″ N and 0°01′07.79″ E) in Ghana with a base elevation of 69 m. Processed meteorological data of AIA were purchased from Trinity Consultants Company (Dallas, TX, USA). Meteorological preprocessor (AERMET) was used to process both the surface and upper meteorological data prior to model simulation. Table 6 indicates the summary of hourly meteorological

Table 2. Residue fluid catalytic cracker unit (RFCCU) data of TOR.

Feed rate [m^3/h]	Air flow rate [Nm^3/h]	Flue gas rate [kg/h]	Catalytic inventory [kg/h]
72	63,883	6239	120,000

Table 3. Example of SO_2 and NO_2 calculations in the flue gas (Affum *et al.* 2016).

Mass of SO_2	Mass of NO_2
Feed stock density = 907 kg/m^3 Feed stock volumetric flow rate = 72 m^3/h Feedstock mass flow rate = 65,322 kg/h Feed sulfur content = 5% Amount sulfur combusted = 5% Mass of sulfur combusted = 32.66 kg Molar mass of sulfur = 32 kg/kmol Amount of sulfur forming SO_2 = 90% Mass of SO_2 formed = 29.39 kg Moles of SO_2 formed = 0.92 kmol $S + O_2 \rightarrow SO_2$ Molar mass of SO_2 produced = 64 kg/kmol Mass of SO_2 produced = 58.88 kg Estimation of flue stack exit gas velocities At pressure = 101.42 kPa Flue gas moles = 2706.83 kmol Flue gas volumetric flow rates = 112,345.89 m^3/h = 31.21 m^3/s Flue stack area = 1.13 m^2 Flue gas velocity = 24.25 m/s	Amount of N in feed stock = 0.32% Feed stock mass flow rate = 65,322.14 kg/h Mass of N = 209.03 kg Amount of combusted feed stock N = 15% Mass of combusted feed stock N = 31.35 kg Molar mass of N = 14 Moles of combusted feed stock N = 2.24 kmol Amount of N producing NO = 90% $2N + O_2 \rightarrow 2NO$ Moles of NO formed = 2.02 kmol Molar mass of NO formed = 30 kg/kmol Mass of NO = 60.47 kg Amount of N forming NO_2 = 10% $N + O_2 \rightarrow NO_2$ Moles of NO_2 produced = 0.22 kmol Molar mass of NO_2 produced = 46 kg/kmol Mass of NO_2 formed = 10.3 kg

Table 4. Stack characteristics used in dispersion modeling study.

Type of stack	Diameter [m]	Height [m]	Exit temperature [K]
Flue	1.28	60	513
Flare	0.60	55	1273

Table 5. Meteorological parameters used in dispersion modeling study.

Surface air	Wind speed [m/s]	Ambient temperature [K]	Sensible heat flux [W/m^2]	Friction velocity [m/s]
Min.–Max.	0.0–49.0	294.2–308.1	64.0–234.5	0.06–5.75
Upper air	Mixing height [m]	Wind direction [°]	Wind speed [m/s]	Temperature [K]
Min.–Max.	10	0–360	0–48.9	294.1–372.9

parameters for the year 2009 at the AIA meteorological station. Land use parameters are shown in Table 7. It is also assumed that the meteorological data for 2009 is similar to 2008 for the study area since there has not been any significant change in weather condition over the years (GMET 2016). A wind rose diagram for year 2009, as shown in Figure 2, was generated for the acquired meteorological data from the AIA meteorological station using METVIEW (version 7.2.4.6).

Table 6. Land use parameters used in dispersion modeling study.

Parameter	Range
Albedo	0.16–1.00
Bowen ratio	0.64
Surface roughness [m]	0.12–0.88

Table 7. Emission parameters used in dispersion modeling study.

Parameters	Flue	Flare
Emission rate [g/s] for SO_2	17.78	24.16
Emission rate [g/s] for NO_2	19.72	0.00
Exit gas velocities [m/s]	24.25	7.66

Note: Flare stack did not emit NO_2 emission.

2.4. Set up of receptor networks

AERMOD (version 7.9.1) with the imbedded AERMET (version 7.8.0.2) and terrain preprocessor (AERMAP) components were used in this study. It is an enhanced version of AERMOD as it accounts for the contribution as well as spatial and temporal distribution of each emission source. The ground level concentration of SO_2 and NO_2 were assessed in the study area within a non-uniform Cartesian receptor network at a radius of 16 km from the sources. A Cartesian receptor grid of a domain size 32 × 32 km grid extending from the source of emissions was used in this study. The nonuniform grid covered 0–5, 5—10, and 10–16 km from the sources with a spacing of 0.2, 0.5, and 1 km, respectively.

2.5. Performance of models validation

With the help of statistical indicators, the accuracies and reliabilities of predicted CALPUFF and AERMOD daily SO_2 and NO_2 levels were assessed with *in situ* measured concentrations. This study employed five statistical indicators to validate the model performances through USEPA guidelines. These included fractional bias (FB), normalized mean square error (NMSE), index of agreement (IOA), geometric mean bias (MG), and geometric mean variance (VG) as shown in Eqs. (1)–(5).

$$\mathrm{FB} = \frac{2\times\left(\overline{C_O} - \overline{C_P}\right)}{\overline{C_O} + \overline{C_P}} \tag{1}$$

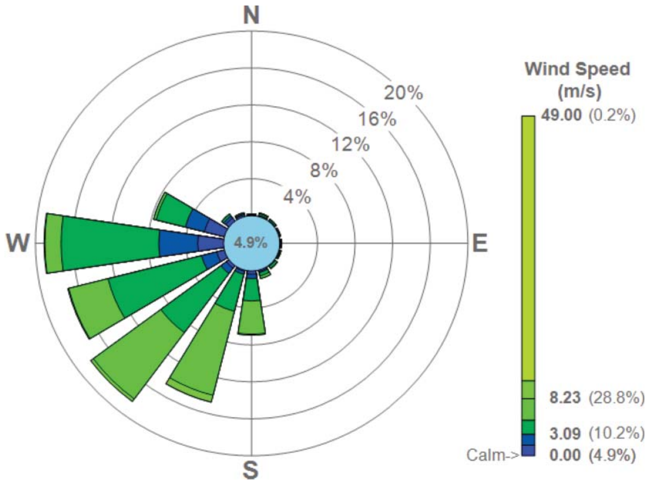

Figure 2. Wind rose in 2009 generated from Accra International Airport (AIA).

$$\mathrm{NMSE} = \frac{\overline{(C_O - C_P)}^2}{\overline{C_O} \times \overline{C_P}} \tag{2}$$

$$\mathrm{IOA} = 1 - \frac{\sum\left(C_P - \overline{C_O}\right)^2}{\sum\left(\left|C_P - \overline{C_O}\right| + \left|C_O - \overline{C_O}\right|\right)^2} \tag{3}$$

$$\mathrm{MG} = e^{\left(\overline{\ln C_O} - \overline{\ln C_P}\right)} \tag{4}$$

$$\mathrm{VG} = e^{\left[\overline{\left(\ln C_O - \ln C_P\right)^2}\right]} \tag{5}$$

where C_P and C_O are predicted and observed concentrations, respectively. $\overline{C_P}$ and $\overline{C_O}$ are the mean values of the predicted and observed concentrations, respectively.

FB is a dimensionless value used to evaluate the biasness of data sets and ranges from +2 to −2. The positive and negative FB values indicate underpredictions and overpredictions, respectively (Chang and Hanna 2004). Also, NMSE measures variance and scattering values between modeled and measured data. Thus, a perfect model will have the FB and NMSE values to be zero (Lee *et al.* 2014). Similarly, the IOA is used to rate the accuracy of models and ranges from 0 to 1. An ideal model will have IOA to be equal to 1 with 0 being the least value. However, IOA value of 0.5 is considered as good (Affum 2015; Lee *et al.* 2014). FB and NMSE are sensitive to be measured and simulated data sets with a narrow range of values (*e.g.*, by a factor of 2 in different). Due to influence in varied meteorological factors, these may lead to a large range of values between modeled and observed data (Chang and Hanna 2004). The MG and VG are more appropriate as they normalize the data sets by log transformation. MG and VG values ensure the balance between the data sets too. A perfect model will have MG and VG values of 1.

3. Results and discussion

3.1. Meteorological observation

Figure 2 shows the wind speed of AIA in 2009 varied from 0.0 to 49 m/s. For about 15.1% of the time within the year, wind speed was less than 3.09 m/s. However, the prevailing wind direction was from W and SW as shown in Figure 2. The minimum and maximum ambient temperatures were recorded to be 294.2 K and 308.1 K, respectively. About upper air characteristics, the mixing height was 10 m and wind direction ranged from 0° to 360° with speed ranges of 0.0 (calm) to 48.9 m/s. The upper air temperatures range from 294.1 to 372.9 K. Solar radiations could be a major factor for mixing of the pollutants within the modeling domain. The study revealed an average sensible heat flux of 149.25 W/m^2 and a friction velocity of 2.9 m/s. The main meteorological parameters are summarized in Tables 5 and 6.

3.2. SO_2 and NO_2 emission rates

Estimation of SO_2 and NO_2 emission rates (g/s) were obtained based on the RFCCU data (Table 2) and material balance approach (Table 3). Table 7 shows that the emission rates of SO_2 in the flue stack was 17.78 g/s and 24.16 g/s in the flare stack. The flue gas contained

19.72 g/s of NO_2; however, analysis of the flare gases did not reveal NO_2 emissions. The exit gas velocities from the flue and flare stacks were 24.25 m/s and 7.66 m/s, respectively.

3.3. Evaluation of CALPUFF and AERMOD models

Twenty-four-hourly field-measured SO_2 and NO_2 concentrations were obtained in the modeling domain over a period of 12 d with the installed Differential Optical Absorption System (DOAS) (Affum 2015; Sackey 2012). The measured values from the DOAS were compared with AERMOD-predicted values from this work and CALPUFF-predicted values recorded by Affum *et al.* (2016). Figure 3 shows overprediction and underprediction of the models with the observed SO_2 and NO_2 values. The results showed that AERMOD could follow the trend and predict the measured values with less sharp changes compared with CALPUFF. This agrees with the basic assumption that AERMOD algorithm assumes the steady state plume dispersion and incorporates vertical wind profile and turbulence (Gibson *et al.* 2013; Kakosimos *et al.* 2011), while CALPUFF is sensitive and suitable in estimation and dispersion of “Puffs” (Rood 2014) and complex terrain (Tartakovsky *et al.* 2016). The AERMOD model results satisfy the above statements, as the model domain is a set of two-point sources and coastal zone with flat terrain (Figure 3).

Despite the visual pattern observed in the plot of the models’ results and field values, it is imperative to evaluate the performance of the models statistically in order to determine their reliability and accuracy with the field-observed values. According to the statistical analysis, the positive values of FB in Table 8 indicate underprediction of both models. The FB values recorded in the CALPUFF model were 0.41 and 0.36 compared with AERMOD values of 0.38 and 0.52 for SO_2 and NO_2, respectively. NMSE values recorded a better value (0.39) in CALPUFF than AERMOD (0.43) for SO_2; however, they showed the opposite good performance of 0.62 compared to 1.34 for NO_2. This shows a reasonable and balanced performance of both AERMOD and CALPUFF with the measured values. Both models reasonably predicted the measured values but not

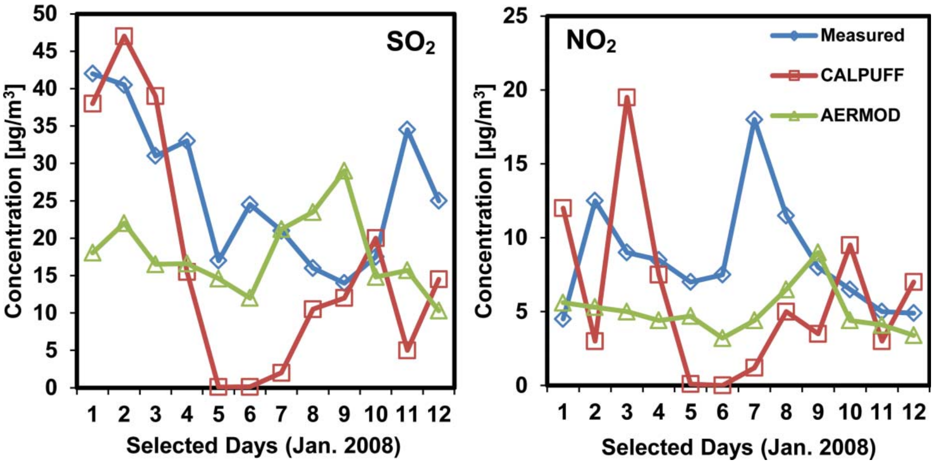

Figure 3. The field-measured values vs. simulated values by CALPUFF and AERMOD for SO_2 and NO_2.

Table 8. Indices performance for CALPUFF and AERMOD validations.

	SO_2					NO_2				
Model	FB	NMSE	IOA	MG	VG	FB	NMSE	IOA	MG	VG
CALPUFF	0.41	0.39	0.73	3.85	1.01	0.36	1.34	0.36	3.45	2.61
AERMOD	0.38	0.43	0.83	1.43	2.04	0.52	0.62	0.87	1.64	1.04

perfectly since FB and NMSE should be zero to be deemed as a perfect model (Chang and Hanna 2004).

IOA values ranged from 0.83 to 0.87 in AERMOD compared with CALPUFF values of 0.36–0.73 (Table 8). Thus, AERMOD performed better than CALPUFF, since values close to 1 represent a perfect model performance (Gibson *et al.* 2013; Lee *et al.* 2014). Such performance could be due to differential wind directions; because, predicted plumes do not overlap with the observed plume irrespective of their similarities in their magnitude. Besides, due to the sensitivity of the instruments, occasional measurements might have been taken prior to plume deposition and such errors might not lead to the normal distribution of measured and simulated values (Chang and Hanna 2004). MG and VG bring about the log transformation of the normal FB and NMSE data to a more balanced one. In this study, MG and VG were better predicted by AERMOD in both SO_2 and NO_2 than CALPUFF, with the exception of VG (1.01), which was better predicted for SO_2 in CALPUFF than in AERMOD (2.04).

To summarize, AERMOD predicted reasonably well in FB, IOA, and MG, while CALPUFF had a better performance in evaluation of NMSE and VG for SO_2. In NO_2, AERMOD had a better prediction with all the statistical performance indices (*e.g.*, NMSE, IOA, VG, and MG) except in FB, which was better in CALPUFF (Table 8).

3.4. Assessment of SO_2 and NO_2 impacts by AERMOD

Table 9 shows the maximum and average concentrations of SO_2 and NO_2 in the study area. The maximum daily SO_2 levels recorded in this study were lower than Ghana EPA (2010) including USEPA (2017) and European Commission (EC) (2016) threshold limits as well (Table 1). Similarly, average hourly and daily levels of NO_2 were lower compared to the standards (Table 1). Also, the annual SO_2 and NO_2 standards issued by World Health Organization (WHO), USEPA, and EC meet estimated AERMOD concentrations within all the receptors (*e.g.*, schools, residential areas, hospitals, parks, etc.) in TOR area (Table 1). This implies that the emissions from TOR did not pose any health threat to the public living and the environment nearby. However, the effect of the modeled SO_2 and NO_2 concentration

Table 9. The maximum and average hourly, daily, and annual concentrations for SO_2 and NO_2.

	Maximum concentration [μg/m^3]		
Indicator	Hourly	Daily	Annual
SO_2	107 (31.2)	38 (4.8)	13.9 (0.93)
NO_2	31.7 (9.3)	9.6 (1.6)	3.6 (0.29)

Note: Average in parenthesis

levels on the sensitive ones (aged, asthmatic, and children) in TOR areas remained unknown. The causes of low ground level concentrations of SO_2 and NO_2 might be due to the usage of low-sulfur content (Ghana Energy Commission 2006) and fine crude oil feedstock by TOR. It could also be due to the location of TOR in close proximity to the coastal zone, where locally derived climatic factors (sea breezes) combined with seasonal Harmattan winds lead to high dilution rates.

3.5. Seasonal distribution and contribution

The effects of seasonal change on SO_2 and NO_2 concentrations and their spatial distributions in the model domain were predicted for the dry season (DS) (January–March), minor raining season (MRS) (September–November), and heavy raining season (HRS) (May–July) as shown in Table 10. The maximum 1 h concentrations for SO_2 and NO_2 occurred during MRS, while maximum daily levels were recorded in HRS. However, the mean concentrations for both pollutants were almost the same for both MRS and DS (Table 10). The concentration levels of hourly and daily SO_2 and NO_2 might be due to the close proximity of the modeling location to the coastal area. The influx of winds from the coast (sea breeze) might cause a reduction in temperatures for all the seasons compared to inland locations of Ghana. However, in DS, SO_2 and NO_2 concentrations were expected to be low due to high solar radiations and wind speeds, causing higher dispersion with lower ground level concentrations compared to the MRS and HRS. Thus, changes in seasonal concentration of the pollutants depended on daily climates, which were influenced by seasonal winds and land-sea breeze (Seangkiatiyuth *et al.* 2011).

Figures 4–6 show seasonal and temporal distribution of SO_2 in TOR areas. The distribution pattern of SO_2 was similar to NO_2 in all of the three seasons (HRS, MRS, and DS). Hence, SO_2 distribution pattern was only presented in the study. During HRS (Figure 4), due to the total absence of Harmattan winds, low solar radiations, and heavy precipitation up to a maximum of 600 mm (GMET 2016), rate of dispersion of the pollutants was lower showing central radial distribution compared to MRS (Figure 5) and DS patterns (Figure 6). These low wind speeds (8.5, 3.5, and 3 m/s for HRS, MRS, and DS, respectively) and low solar radiations might cause a high concentration of daily pollutants in HRS (Table 10). It is therefore evident that the dispersion of pollutants is greatly affected by the local meteorological factors (strength and frequency of wind, the intensity of solar radiations) and land surface features (Lee *et al.* 2014). MRS distribution patterns of the pollutants shifted southward, but somewhat centered in southeastern and northeastern directions. MRS showed the highest maximum hourly concentration of the pollutants in the modeling domain due to lack of Harmattan winds (Table 10). In the case of TOR areas, heavy land-sea breezes might have also influenced the distribution of the pollutants as

Table 10. Maximum seasonal hourly and daily SO_2 and NO_2 concentrations of TOR area.

	Maximum hourly [$\mu g/m^3$]		Maximum daily [$\mu g/m^3$]	
Seasons	SO_2	NO_2	SO_2	NO_2
Heavy rain season (May–Jul)	101.9 (25.1)	28.9 (7.8)	37.7 (4.3)	9.6 (1.4)
Minor rain season (Sep–Nov)	107.4 (24.1)	31.7 (7.0)	32.8 (3.3)	9.6 (1.1)
Dry season (Jan–Mar)	103.9 (24.2)	30.9 (7.0)	31.5 (3.3)	8.9 (1.0)

Note: Average in parenthesis.

Figure 4. Distribution patterns of maximum hourly SO_2 emissions during HRS in TOR area.

most of the pollutants in MRS tend to move toward the sea (Figure 5). The study showed that the concentration of air pollutants might be reduced in the modeled location during MRS (from September to November). Contrastingly, in DS, the pollutants moved linearly from their emission sources toward northward direction. While, SO_2 (54–64 $\mu g/m^3$) and NO_2 (12–18 $\mu g/m^3$) were diffused evenly within northeastern and southeastern directions (Figure 6). This happened due to the lack of precipitation and the presence of strong winds during the DS. As far as future exposure and epidemiological studies in the Tema Metropolis are concerned, residents living in west northern and southern part of TOR areas may be exposed to least SO_2 and NO_2

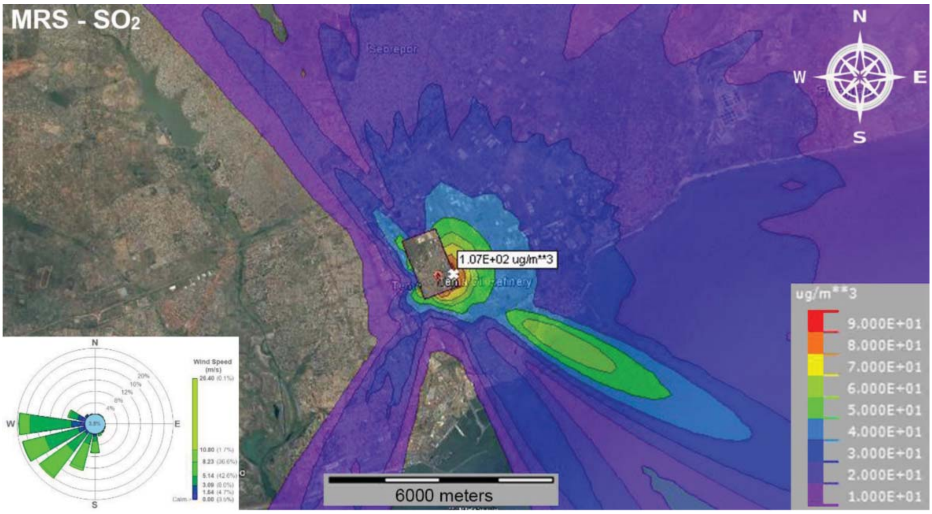

Figure 5. Distribution patterns of maximum hourly SO_2 emissions during MRS in TOR area.

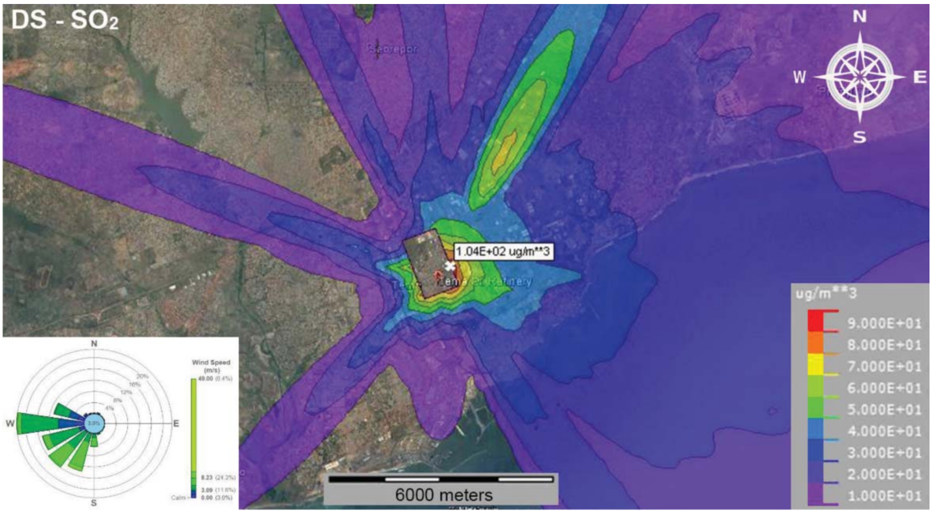

Figure 6. Distribution patterns of maximum hourly SO_2 emissions during DS in TOR area.

levels compared to those in opposite direction (Figures 4–6). Thus, different seasonal distribution patterns may lead to different health effects to the exposed population.

4. Conclusions

This study employed the USEPA-regulated AERMOD modeling system to estimate SO_2 and NO_2 emissions from flue and flare stacks in the surrounding areas of TOR. Five performance indices were utilized to understand and assess the reliability and the accuracy level of AERMOD and the reported CALPUFF results of the same data from TOR. The results showed that the performance of AERMOD in the prediction of measured values was better than that of CALPUFF. In other words, the performance of AERMOD agreed with the observed values with three statistical indices against two indices for CALPUFF in SO_2 and four indices against one for NO_2. AERMOD model results predicted that the concentrations of pollutants were within the acceptable limits for both local and international standards. Pollutant dispersions were assessed for three seasons with distinct meteorological conditions, which were the main determinants of SO_2 and NO_2 levels in the study area. The model results showed slight variations in concentration of the pollutants with respect to the local Harmattan wind and sea breeze factors within the seasons; however, they showed significant variability in their distributions. Although, there were a number of limitations associated with this study, the AERMOD could yield reliable results of future health risk assessment projects within the Tema Metropolis and its surrounding locations. The results of this study can be used both in providing a fair understanding about the concentration of pollutants and in future epidemiological studies within the metropolis.

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ORCID

Hamid Omidvarborna http://orcid.org/0000-0003-2865-5319

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