ENVIRONMENTAL HEALTH | RESEARCH ARTICLE

Atmospheric dispersion modeling of uncontrolled gaseous pollutants (SO$_2$ and NO$_x$) emission from a scrap-iron recycling factory in Ile-Ife, Southwest Nigeria

O.E. Abiye*, L.A. Sunmonu*, A.I. Ajao*, O.E. Akinola*1, M.A. Ayoola* and O.O. Jegede*

Abstract: In the last decade, government policies promoting foreign investments in the industrial sector particularly for small and medium scale enterprises in Nigeria have led to increased establishment of scrap-iron recycling factories in many states of the federation. Albeit the economic benefits in terms of waste material sourcing and job creation, these scrap-iron recycling factories have attracted significant public criticism due to the characteristic uncontrolled pollution (toxic gases) plume released from their operations into the atmospheric environment of host communities and thus aggravating existing and unresolved rural and urban air pollution problems in Nigeria. This study therefore provides model-based estimates of atmospheric dispersion for gaseous pollutants (SO$_2$ and NO$_x$) released from a scrap-iron recycling factory located in Ile-Ife, southwest Nigeria as a case study for investigating emission signature from such sources. Meteorological parameters measured at the factory location in 2012 and 2013 were used to execute U.S recommended short range (<50 km) Gaussian-based regulatory air pollution dispersion model (AERMOD: American Meteorological Society/Environmental Protection Agency Regulatory Model, v12060). Isopleths of maximum concentration values for 1 h averaging

ABOUT THE AUTHOR

The author is a Research Fellow at CERD and an Associate Lecturer in the Department of Physics & Engineering Physics both in Obafemi Awolowo University Ile-Ife, Nigeria. His PhD research was on "Meteorological Modeling and Atmospheric Dispersal of Gaseous Effluents from a Scrap-Iron Recycling Factory in Ile-Ife, Southwest Nigeria". He has interest in air pollution meteorology, monitoring/ion beam characterization of PM, and air pollution modeling. He is currently participating as a project scientist in the on-going EU-funded Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa (DACCIWA) field campaign.

PUBLIC INTEREST STATEMENT

As part of research efforts to understand the contribution of various industrial sources to atmospheric pollution burden across Nigeria, this study applied AERMOD model to obtain estimates of the concentrations for gaseous pollutants released from the operations of a scrap-iron recycling factory. Maximum 1 h averages of concentration values obtained from AERMOD were less than the NAAQS allowable limits (200 μgm$^{-3}$). Temporal analysis of the monthly variation however indicated that early morning hours have high potential for the occurrence of elevated concentrations levels above the set limits. The results of this study will be useful in assessment of emission source signatures that is needed by environmental standard and regulatory agencies, policy-makers and private stakeholders for planning and evaluation of the long-term effects of such industrial gaseous releases and consequently protect public health.

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period were projected to occur within 1.5 km radius from the factory in SW and NW directions during early morning hours (02:00–06:00 h (GMT + 1)). Prevailing meteorological conditions during periods of maximum concentration were characterized by stable atmosphere \(dT/dz\ (>0.01°C/m), \) very weak winds (<1.5 ms\(^{-1}\)), low mixing height (<200 m) and high relative humidity (>90%).

Subjects: Atmospheric Sciences; Environmental Issues; Environment & Health; Environmental Change & Pollution; Environmental Physics

Keywords: meteorology; atmospheric dispersion; AERMOD; scrap-iron recycling; air pollution; toxic corridor

1. Introduction

In recent years, several cities in the West African sub-region have reportedly experienced significant increase of anthropogenic emissions of air pollutants (Assamoi & Liouesse, 2010; Butler et al., 2008) due to increase in human population. Particularly in Nigeria, explosive population growth and its attendant rural-to-urban migration coupled with industrial expansions have lead to excessive emission of wide range of toxic gaseous pollutants including \(\text{SO}_2\), \(\text{NO}_x\), and \(\text{CO}\) into the atmospheric environment (Li et al., 2014). Several epidemiological and toxicological studies (Mortimer, Neas, Dockery, Redline, & Tager, 2002; Moshammer, Hutter, Hauck, & Neuberger, 2006; Peacock et al., 2003; Peel et al., 2005) have shown that short- and long-term exposures to gaseous pollutants such as \(\text{SO}_2\), \(\text{NO}_x\), and \(\text{CO}\) have adverse effects on human health and the environment (flora and fauna). \(\text{NO}_x\) and \(\text{SO}_2\) are known to increase susceptibility to respiratory infections among children and elderly and also increase airway responsiveness in asthmatic individuals (European Union, 2014). CO is known to cause tissue hypoxia thereby reducing the blood capacity to transfer oxygen (Kampa & Castanas, 2008). In the long run, continuous exposures to these gaseous pollutants concentrations lead to respiratory and cardiovascular morbidity, and eventually, increased mortality rate. It is however highly disturbing that in Nigeria these gaseous pollutants, considering the extent of their health impact, are mostly released into the environment in an uncontrolled and unregulated manner (Knippertz et al., 2015) from most small- and medium-scale enterprises (SMEs) industrial facilities. The inability of the government to provide a regulatory framework to monitor and sanction uncontrolled release of pollutants from industrial facilities has been a major setback in curtailting the abuse on the environment and hence the consequences on human health. This problem is exacerbated by lack of \textit{in situ} measurements to monitor pollutants concentrations due to fiscal, temporal, and spatial constraints at all possible locations of interest. As such, there is dire lack of reference information for appropriate air quality policy and planning in Nigeria (Ezeh, Obioh, Asubiojo, & Abiye, 2012; Obioh et al., 2013). In the absence of \textit{in situ} air quality measurements, an efficient and cost-effective alternative approach is the use of well-tested and validated regulatory air pollution dispersion models to estimate pollutants concentrations at different spatial resolutions (Filip Soporan, Nascutiu, Soporan, & Pavai, 2015; Gibson, Kundu, & Satish, 2013; Johnson, Isakov, Touma, Mukerjee, & Özkan, 2010; Podrez, 2015; Trapp, 2010; Wang & Chen, 2008).

As part of research efforts to understand the contribution of various industrial sources to atmospheric pollution burden across Nigeria, this study applied the American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD), an advanced Gaussian-based regulatory air pollution dispersion model, to obtain estimates of the concentrations for gaseous pollutants released from the operations of a scrap-iron recycling factory located in Fashina (7°29'N, 4°28'E, 262 m a.s.l), a suburb of Ile-Ife in southwest Nigeria. To ensure the plausibility of the AERMOD concentration estimates, site-specific meteorological measurements made near the factory has been used to drive the model run. This was with a view to ensuring that pollutants concentration estimates obtained will serve as a basis for ensuring that exposure limits known to safeguard human and environmental well-being of the host community are not exceeded as well as enforcing known air quality regulatory guidelines for industrial facilities violating stipulated threshold limits.
2. Methodology

2.1. Source characteristics at the study site

The scrap-iron recycling factory was located in Fashina (Figure 1), an agrarian community off the Ife-Ibadan expressway. The location was about 8 km, as the crow flies, from the foremost academic institution in Nigeria; the Obafemi Awolowo University, Ile-Ife. The factory is a private smelter facility established in 2011 and it was the only industrial activity of its kind in the area (radius of 50 km). At the time of this study, the factory has no installed stacks. As such, emissions from the factory into the atmosphere were completely uncontrolled, escaping through orifices along the length and breadth of the building mostly at the rooftop. It has a physical dimension of about 305 m × 228 m × 20 m and was modeled assuming a volume source configuration. The factory has two installed Electric Arc Furnaces (EAF) which were operated interchangeably with an average of four batch process (heat cycle) completed every 24 h during a night and day shift. Each batch process is a sequence of many stages which includes charging, melting, refining, slagging, tapping, and casting. Typically, the input material into the EAF is hundred percent ferrous- and/or metal-containing scraps gathered from various sources by scavengers. The EAF is a cylindrical, refractory-lined container into which carbon electrodes are lowered or retracted. When the electrodes are retracted, scrap metals are then charged (placed) into the EAF by overhead crane. Direct-reduced iron (DRI) or other iron-bearing materials are supplemented to aid the scrap metals used as charge material. During the refining process, impurities which are incompatible with in the molten metal are removed as slag from the top. Chemically, the slag layer consists primarily of oxides of calcium, iron, silicon, phosphorus, sulfur, aluminum, magnesium, and manganese in complexes of calcium silicates, aluminosilicates and aluminoferrite. The molten steel is then tapped into preheated ladles and transferred to the continuous casting shop after purging and addition of ferroalloys. It is in these processes that gaseous pollutants (e.g. NOx and SO2) and particulate matters are emitted at varying degrees. Sixteen hours were estimated as the active operating duration per day during which pollutants are released into the atmosphere. Having identified the emissions from the scrap-iron recycling factory as an uncontrolled volume source, estimates of the source characteristics were needed. The most important source characteristics required by AERMOD to execute model run for a volume source are emission rate $E$ in g s$^{-1}$, initial lateral dimension $\sigma_y$ and initial vertical dimension $\sigma_z$ of the volume (USEPA, 2004). This study employed the emission factor procedure laid out in USEPA AP-42 documents (USEPA, 1995) to estimate the source emission rate. This was because source-specific emission factor measurements were not available for the factory. As such, the AP-42 methodology provides the best and most frequently adopted alternative for emission rate estimations. Datasheets documenting weight of daily material input (molten scrap metals, alloying agents and fluxing materials) and total tones of billets produced for each batch process

![Figure 1. Map showing the study location and the modeling domain around the scrap-iron recycling factory.](image-url)
were averaged to obtain total material processed per day. The total material processed was taken as the activity rate of the recycling operations and the emission factors for the gaseous pollutants were taken from the AP-42 document for uncontrolled releases from an EAF. \( \sigma_{yo} \) and \( \sigma_{zo} \) were estimated following the procedure for a volume source configuration (USEPA, 2004). The following assumptions were made in obtaining estimate of the source emission rate; (i) pollutants emission occurs at two points in the process line: during charging of scrap metal in the EAF and during refining process in the ladle, (ii) emissions from aggregate material handling, storage piles, paved and unpaved road traffic were considered insignificant, (iii) information on the randomly selected datasheets used in compiling activity rate are representative of the daily operation at the recycling factory. Although assumptions made may introduce certain degree of uncertainty in the emission rate estimate (Piotr & Nahorski, 2015), it does not limit its applicability for regulatory purposes (USEPA, 2004).

### 2.2. Meteorology and surface layer parameters

Near surface meteorological data-set for the periods, September–December 2012 and March–December 2013, was obtained from a site-specific meteorological mast installed near the scrap-iron recycling factory. The data-set includes gradient measurements of wind speed (at 1.5 and 5.5 m), air temperature and relative humidity (each at 1 and 5 m), single level measurements of net radiation (1.5 m), soil heat flux (5 cm depth), and wind direction (5.5 m). All the sensors for the measurement were instrumented to a 6 m meteorological mast and connected via cable to a Campbell Scientific datalogger (model CR1000). The data obtained were sampled at 10 s and stored as 10 min averages. This was later reduced to hourly averages, a necessary requirement for the AERMOD. Deterministic surface layer parameters such as Bowen ratio, friction velocity, Monin-Obukhov length, convective velocity scale, mixing height, albedo, roughness length, and sensible heat flux required by the AERMOD were estimated from tested and validated empirical relationships.

The Bowen ratio \( \beta \) (Kakosimos, Assael, Lioumbas, & Spiridis, 2011), the ratio of sensible heat flux (\( H \)) to latent heat flux (\( \lambda E \)), was estimated from the gradient of air temperature (\( T \)) and specific humidity (\( q \)) as follows:

\[
\beta = \frac{H}{\lambda E} \equiv \frac{\gamma \Delta T}{\Delta q}
\]  
(1)

where \( \gamma \) is the psychometric constant (0.4 g/kg·K\(^{-1}\)). \( \Delta T \) and \( \Delta q \) are gradients of air temperature and specific humidity, respectively. In order to obtain the specific humidity, an estimate of the saturated vapor pressure and vapor pressure is required. A polynomial approximation method by Lowe (1977) was adopted. From surface energy balance equation (Oke, 1978), the Bowen ratio energy budget method (BREB) (Van Ulden & Holtslag, 1985) was used in conjunction with measured net radiation flux and soil heat flux to obtain the sensible heat flux as follows:

\[
H \approx \frac{(R_N - G)}{1 + 1/\beta}
\]  
(2)

The convective velocity scale \( (\omega_c) \), a measure of thermal turbulence transport in the boundary layer, was estimated following the formulation of Deardorff (1970) cited in Cimorelli et al. (2004a) as follows:

\[
\omega_c = \left( \frac{g H}{T \rho C_p z_c} \right)^{1/3}
\]  
(3)

The convective \( (z_c) \) and mechanical \( (z_m) \) mixing heights were estimated based on Giovannoni (1993) and Venkatram (1980), respectively, as:

\[
z_c = -kL \left( \frac{\omega_c}{u_c} \right)^3
\]  
(4)

\[
z_m = 2300u_c^{3/2}
\]  
(5)
2.3. Dispersion modeling

A window-based version of the AERMOD obtained from USEPA office (website) was executed for estimating pollutant concentrations from the scrap-iron recycling factory. The Gaussian-plume formulation was based on the assumption of steady-state conditions. The meteorological conditions were assumed to remain constant during the dispersion from source to receptor, which was effectively instantaneous. Emissions rates and meteorological conditions can vary from hour to hour but the model calculations in each hour are independent of those in previous or subsequent hours (Cimorelli et al., 2004b). Thus, the AERMOD simulates hourly averages of pollutants concentrations. Depending on the atmospheric stability and the height at which plume was released within or above the boundary layer, the model incorporates algorithms for simulating different plume types (Venkatram, Isakov, Pankratz, Heumann, & Yuan, 2004). During convective conditions, the total concentration \( C_c \) distribution produced by AERMOD results from a combination of three plume types: direct \( C_d \), indirect \( C_i \), and penetrated \( C_p \), as follows:

\[
C_c = C_d + C_i + C_p
\]

\[
C_d(x, y, z) = \frac{Q_f}{\sqrt{2\pi \sigma_y}} \sum_{i=0}^{\infty} \frac{\lambda_i}{\sigma_y} \left[ \exp \left( \frac{-(y - \psi_{d_i})^2}{2 \sigma_y^2} \right) \right]
\]

\[
C_i(x, y, z) = \frac{Q_f}{\sqrt{2\pi \sigma_y}} \sum_{m=1}^{\infty} \frac{\lambda_m}{\sigma_y} \left[ \exp \left( \frac{-(y - \psi_{i_m})^2}{2 \sigma_y^2} \right) \right]
\]

\[
C_p(x, y, z) = \frac{Q(1 - f_p)}{\sqrt{2\pi \sigma_y}} \sum_{m=0}^{\infty} \frac{\lambda_m}{\sigma_y} \left[ \exp \left( \frac{-(y - \psi_{p_m})^2}{2 \sigma_y^2} \right) \right]
\]

where \( F_y, \psi_y, \sigma_y \), and \( \lambda \) are lateral distribution function, effective source height, vertical dispersion parameter and weighting coefficient respectively. \( F_x \) and \( \psi_x \) are defined as:

\[
F_y = \frac{1}{\sqrt{2\pi \sigma_y}} \exp \left( -\frac{y^2}{2 \sigma_y^2} \right)
\]

\[
\psi_{d_i} = h_i + h_p + \frac{w_f}{u} x
\]

where \( h_i \) the physical stack height; \( \frac{w_f}{u} x \) is the contribution to plume rise due to ambient turbulence; \( \Delta h_p \) is momentum-buoyancy superimposed plume rise and is given as:

\[
\Delta h_p = \left( \frac{3F_m}{\beta^2 u^2} + \frac{3F_p x^2}{2 \beta^2 u^3} \right)^{1/3}
\]

Details of the AERMOD formulations are discussed in Cimorelli et al. (2004a, 2004b).

In this work, the preference for AERMOD over other dispersion models (Holmes & Morawska, 2006) was guided by its robustness, availability for use, and widespread recommendation for regulatory...
purposes (Hoinaski, Franco, & de Melo Lisboa, 2016). It is robust in the sense that the formulations of the AERMOD model are consistent with the random nature of turbulence in the atmospheric boundary layer and can predict with high reliability the dispersion of continuous, buoyant plumes within short distances up to about 50 km. Also, the model has been extensively tested and validated for assessment of air pollution sources both in rural and urban air shed (Perry et al., 2003; Podrez, 2015; Tartakovsky, Broday, & Stern, 2013). In its execution, the image runstream was structured to simulate default regulatory option in a flat terrian. Since the topography of the modeling domain is fairly flat, receptors terrain elevations were not incorporated into the image runstream due to unavailability of terrain data needed to generate hill height scale parameters. As such, this study considered the variation in the receptors terrain elevation within the modeling domain as insignificant and thus neglects its effect on the model output.

2.4. Modeling domain

Having considered the prevailing wind ventilation corridor during the measurement period, an equally spaced receptor network placed at 200 m apart covering a horizontal and lateral distance of approximately 8 km by 6 km, respectively, was used as the domain of interest on the receptor pathway. A scaled map of the modeling domain (Figure 1) featuring Obafemi Awolowo University and residential areas was used as base map on which pollutants dispersion from the scrap-iron recycling factory was overlayed for spatial visualization of concentration distributions. The scrap-iron recycling factory located southwest of the modeling domain was at a point \((x = 3,200 \text{ m}, y = 1,700 \text{ m})\) and at about 245 m (a.s.l) on the gridded domain.

2.5. Sensitivity analysis

Sensitivity analysis of the AERMOD model to input variables (meteorological parameters and surface characteristics listed in Table 1) measured at the study location was carried out. Several model runs were made to probe the sensitivities for 1 h averages of NOx concentration within the range of values indicated in Table 1 for September–December, 2012 and for all receptor locations in the modeling domain.

3. Results and discussion

3.1. Variation of measured meteorological parameters

Diurnal variation of hourly values (floating columns) and period averages (line plots) for the meteorological parameters measured at the study location are presented in Figures 2 and 3. The parameters includes air temperature (5 m), relative humidity (5 m), soil heat flux and net radiation flux. In 2012, daytime air temperature varied between a minimum values of about 18.0°C around 12:00 h (GMT + 1) and a maximum of 35.0°C around 15:00 h. It was observed from the figures that the air mass near the surface was much warmer between sunset (18:00 h) and midnight (00:00 h) than during early morning periods (00:00–06:00 h). Relative humidity values were mostly above 90% at night and as low as 20% during daytime (Figures 2(b) and 3(b)). Daytime net radiation flux at the surface reached peak values of between 678 and 758 Wm\(^{-2}\) with minimum nighttime values of about −85 and −70 Wm\(^{-2}\), respectively, for 2012 and 2013 (Figures 2(c) and 3(c)). Maximum soil heat flux values of about 188 and 232 Wm\(^{-2}\) and minimum values of −87 and −134 Wm\(^{-2}\) were recorded in 2012 and 2013, respectively (Figures 2(d) and 3(d)). These observations are attributed to the
consequences of the reversal in the thermal exchanges that occur at the ground surface shortly after sunset. After sunset when incoming solar radiation was totally absent, the ground surface began to cool by releasing thermal energy to the surface. The cooling process at the ground surface continued through midnight and early morning hours when the thermal exchange would have reached a threshold. This implied that less thermal energy was available at the surface to enhance the buoyancy of air parcels for dispersing pollutants species during the early morning period and portends favorable condition for elevated concentrations.

3.2. Model projection of concentrations and dispersion

From the emission factor methodology employed in this study, an estimated value of 160 tonnes for total material production per day (i.e. molten metal from the ladle and finished steel) was obtained at the factory. Emission rates for SO$_2$ and NO$_x$ were estimated to be 0.3737 and 0.4487 g s$^{-1}$, respectively. Values of $\sigma_y$ and $\sigma_z$ obtained were 70.93 and 9.30 m, respectively, with a release height of about 20 m. From these source parameters, the concentration isopleths obtained for the first-highest 1 h averages of SO$_2$ and NO$_x$ in 2012 and 2013 are presented in Figures 5 and 6, respectively. From the pollutants concentration isopleths, a clear distinction can be observed between the model-predicted atmospheric dispersion of SO$_2$ and NO$_x$ in both years. These distinctions are consequences of the dynamical changes in the atmospheric conditions observed in each year and are discussed below.

In 2012, the wind was blowing predominantly from the SW (11%), W (13%) and WSW (17%) directions. These imply that the pollutants are distributed in the NE, ENE, and E directions, respectively, and thus making locations within these corridors highly susceptible to elevated pollution concentrations. Presented in Figure 4(a) are the wind roses depicting the wind flow characteristics at the study location. Statistics of the wind speed frequencies are given in Figure 4(b) and (c). Specifically, wind speeds greater than 3.0 m s$^{-1}$ (recorded about 1.3% occurrence) were confined to the WSW and W flow directions. These relatively high wind speeds in these directions enhance the horizontal advection of pollutants along the ventilation corridors thus increasing the number of locations impacted by 60–80 μg m$^{-3}$ concentration levels (Figure 5(a) and (b)). Wind blowing from the NE and SE of factory contributed between 1 and 9% to the flow corridors at the location. These north- and
south-easterly flows, though minimal in occurrence, contribute significantly to the ventilation of the pollutants toward the NW and SW of the modeling domain. These can be attributed to the dispersion of about 80–100 μgm⁻³ of NOₓ and SO₂ in those directions as observed from the concentration isopleths for 2012. The O.A.U. Campus, with a population of over 30,000, was predicted to be exposed to concentration levels of about 20–40 μgm⁻³ of NOₓ and SO₂.

Maximum concentration values for NOₓ (201.5 μgm⁻³) and SO₂ (167.8 μgm⁻³) were estimated to occur at a location (x = 3,000 m, y = 1,800 m on the modeling domain) about 500 m northwest of the factory. The maximum values were projected to occur on 24th November 2012 at about 03:00 h (GMT + 1). The wind was observed to be blowing from the southeast direction (117°) at the time of occurrence of these maximum concentrations with a mean wind speed of 0.46 ms⁻¹. Wind originating from this direction contributed about 4% to the flow at the study location and the resultant dispersion corridor was toward the northwest. This explained the direction of the observed maxima from the scrap-iron recycling factory. The estimated atmospheric mixing height was barely 100 m with a relative humidity of 92% indicating an almost saturated atmosphere. Observed air temperature at the surface was 21.8°C, the minimum recorded for the day. The meteorological conditions recorded for this period indicated a highly inhibitive atmosphere to pollution dispersion thereby enhancing the probability for the occurrence of elevated concentration. Further, analysis of stability conditions using the methods of temperature gradient (dT/dz) and standard deviation in the fluctuation of horizontal mean wind (σθ) shows that the atmosphere was stable during the period. Precisely, estimated values obtained for static stability dT/dz and dynamic stability σθ were −0.013°C/m and 6.72, respectively. These values were within documented stability classifications for a moderately stable atmosphere (Beychok, 2005; Mohan & Sadiqqui, 1999). From the model estimate, locations within 1.5 km radius from the scrap-iron recycling factory received between 100 and 200 μgm⁻³ (enclosed within red isopleths in Figure 5(a) and (b)) of pollutants concentration. The occurrence of high concentration level at short distances from the factory could be attributed to the prevalence of weak wind speed at the location. For instance, wind speed between 0.5 and 2.0 ms⁻¹ contributed more than 70% to the flow characteristics at the location (see Figure 4(b)). This implied that horizontal advection of pollutants...
The toxic corridors projected for NO\textsubscript{x} within the modeling domain were observed to cover wider area than for SO\textsubscript{2}. This was attributed to the differences in the emission rates of SO\textsubscript{2} and NO\textsubscript{x}. From the emission rates presented earlier, the amount of NO\textsubscript{x} released from the factory into the ambient air was 20\% more than SO\textsubscript{2}. The 98th percentile concentration values of 133.2 \mu gm^{-3} obtained for NO\textsubscript{x} (see Table 2) were well below the primary exposure limit stipulated by the USEPA National Ambient Air Quality Standard (NAAQS). The USEPA set the primary limit at 100 ppb (~187.7 \mu gm^{-3}) for NO\textsubscript{x} (Podrez, 2015; USEPA, 2014). For SO\textsubscript{2} on the other hand, the primary limit was set at 75 ppb (~165.3 \mu gm^{-3}) of 99th percentile concentration. Although the threshold limits were not exceeded, the range of maximum concentration values obtained for the study domain indicated tendencies of possible violation at location not far from the factory.
Figure 5. Isopleth of concentration distribution for SO₂ and NOₓ dispersion in 2012.

Table 2. Maximum and percentile distributions of estimated concentrations

| (μgm⁻³) | 2012 | 2013 |
|---------|------|------|
|         | SO₂  | NOₓ  | SO₂  | NOₓ  |
| Maximum (percentile) | 167.8 | 201.5 | 157.3 | 188.9 |
| 1       | 21.2 | 25.5 | 3.2   | 3.9   |
| 5       | 25.2 | 30.3 | 3.7   | 4.4   |
| 10      | 28.2 | 33.9 | 4.2   | 5.0   |
| 25      | 34.9 | 42.0 | 5.9   | 7.0   |
| 50      | 42.5 | 51.0 | 33.7  | 40.4  |
| 75      | 55.5 | 66.6 | 65.4  | 78.5  |
| 90      | 72.0 | 86.5 | 82.2  | 98.7  |
| 95      | 84.0 | 100.9| 91.9  | 110.4 |
| 98      | 110.9* | 133.2 | 105.9* | 127.2 |

*Values with 99 percentile.
The concentration isopleths obtained for 2013 presented in Figure 6 showed an atmospheric dispersal of pollutants that was completely different from the previous year due to prevailing wind flow pattern. The wind was blowing from between W and SW directions only (Figure 4(a)). These wind flows have dispersion corridors toward E and NE directions from the factory. This explained the observed model projections of pollutants dispersion shown in Figure 6. The maximum concentration values for SO\textsubscript{2} (157.3 μgm\textsuperscript{-3}) and NO\textsubscript{x} (188.9 μgm\textsuperscript{-3}) were estimated to occur on 19th October 2013 at about 04:00 h (GMT + 1) with 249° as the value of the prevailing wind direction. These values occurred at a location (x = 3,400 m, y = 1,800 m) about 400 m further away from the factory than that of the previous year. Although the stability conditions at the time of maximum concentration occurrence were similar to those of 2012, the boundary layer parameters were characterized by a more inhibitive atmosphere. For instance, the estimated mixing height was barely 40 m at the time and relative humidity was 94% in addition to a very low wind speed of 0.29 ms\textsuperscript{-1}. Clearly, horizontal advection of pollutants species from the factory would be greatly limited under such condition and accounted for higher concentrations estimated near the source. However, locations exposed to at least 100 μgm\textsuperscript{-3} of pollutants concentration covered wider area than in 2012 (within red isopleths in Figure 6).
Figure 6). This was because the ambient air temperature was higher (24.2°C) than in 2012 (21.8°C). Atmospheric diffusion would therefore be enhanced due to enhanced buoyancy of pollutants species. Similar observations were reported by Iorga, Raicu, and Stefan (2015) at a suburban location near an industrial plant in Bucharest, Romania. From the two years of meteorological measurement and atmospheric dispersal of pollutants simulated in this study, the average concentration of NOx and SO2 impacting on the Obafemi Awolowo University community was projected to increase from 40 μgm−3 in 2012 to about 80 μgm−3 in 2013. In addition, the public primary school located in the NE direction of the factory across the busy expressway and some residential buildings in the area were projected to continuously lie within the epicenter of high concentration levels at all times. These locations are high risk toxic corridors and are considered unsafe. Monthly statistics of the distribution of NOx shown in Figure 7 reveals higher estimates of concentration occurred in the months from November 2012 to May 2013 having maximum values between 180 and 230 μgm−3. Over the modeling domain, all the months had an estimated mean values less than 50 μgm−3 except for the October and November 2012. The model projections for NOx distribution from June to December 2013 were quite similar with no significant difference in the estimated maximum values.

### 3.3. Model sensitivity analysis

The result of the sensitivity test is summarized in Table 3. In this study, it was observed that most sensitivity parameter is roughness length. Within the perturbation range tested, a linear response

| Parameter          | Variation limits | Max change (μgm−3) | Max change (%) |
|--------------------|------------------|--------------------|----------------|
| Air temperature    | −6°C             | 11                 | 5              |
|                    | +6°C             | 11                 | 5              |
| Albedo             | 0.5 rνx          | nil                | nil            |
|                    | 2 rνx            | nil                | nil            |
| Roughness length   | 0 m              | 16                 | 8              |
|                    | 5 m              | 3                  | −2             |
| Net radiation      | 0.25 rνx (m−2)   | Insignificant      | <0.5           |
|                    | 4 rνx (Wm−2)     | Insignificant      | <0.5           |
was observed to exist between the roughness length and the estimated concentration. Generally, an increase in the roughness length reduces the maximum average concentration of NO2 by about 3 μgm−3 which was approximately a 2% drop in the pollution level. On the other hand, when the model was tested for a scenario with no roughness elements (roughness length = 0), the maximum average concentration increased by about 16 μgm−3 indicating a possibility of up to 8% rise in modelled pollution level. The model showed a nonlinear response to air temperature variations. At both extremes (±6°C), the maximum average concentrations were about 5% more than the base value.

4. Conclusion
Preprocessed site-specific meteorological data coupled with the AERMOD, a Gaussian-based advanced regulatory air pollution model have been used to drive the simulation of atmospheric dispersal of NO2 and SO2 from a scrap-iron recycling factory in Ile-Ife, southwest Nigeria. Maximum 1 h averages of concentration values obtained from the AERMOD were less than the allowable limits (200 μgm−3). Temporal analysis of the monthly variation however indicated that certain periods of the day between 02:00 and 06:00 h (GMT + 1) might experience the occurrence of elevated concentrations levels above the limits. Sensitivity analysis of the AERMOD model to air temperature, net radiation, albedo, and roughness length reveals that the model was most sensitive to perturbation of surface roughness length; with an estimated 8% increase of concentration level in the absence of roughness elements. The study concludes that locations within 1.5 km radius from the scrap-iron recycling factory were most susceptible to the impacts of the gaseous releases from the factory's operations.

Acknowledgments
Authors are grateful for the financial support, meteorological sensors and human resources provided by the Atmospheric Physics Research Group (APRG, led by Prof. O.O. Jegede) in the Department of Physics and Engineering Physics, Obafemi Awolowo University, Ile-Ife, Nigeria. Free access given to researchers for the use of AERMOD by the U. S. Environmental Protection Agency is well appreciated.

Funding
The authors received no direct funding for this research.

Author details
O.E. Abiye1
E-mails: waleabiye@gmail.com, eabiye@cerd.gov.ng
ORCID ID: http://orcid.org/0000-0002-8601-2242
1 Centre for Energy Research and Development, Obafemi Awolowo University, Ile-Ife, Nigeria.

M.A. Ayoola2
E-mail: akinolaoe@gmail.com
O.E. Akinola2
E-mail: iyiolamercy2005@yahoo.com
O.O. Jegede2
E-mail: oojegede@yahoo.com
2 Atmospheric Physics Research Group, Department of Physics and Engineering Physics, Obafemi Awolowo University, Ile-Ife, Nigeria.

L.A. Sunmonu3
E-mail: sunmonula@yahoo.co.uk
A.I. Ajao4
E-mail: ajao1400@yahoo.com
O.E. Abiye1
E-mail: oabiye@cerd.gov.ng
ORCID ID: http://orcid.org/0000-0002-8601-2242
3 Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, Nanjing University of Information Science and Technology, Nanjing, China.

Citation information
Cite this article as: Atmospheric dispersion modeling of uncontrolled gaseous pollutants (SO2 and NOx) emission from a scrap-iron recycling factory in Ile-Ife, Southwest Nigeria, O.E. Abiye, L.A. Sunmonu, A.I. Ajao, O.E. Akinola, M.A. Ayoola & O.O. Jegede, Cogent Environmental Science (2016), 2: 1275413.

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