UNIVERSITY OF ZIELONA GÓRA

CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2025; 35 (4): 0091-0115
DOI: 10.59440/ceer/208943
Original Research Article

GAS FLARING AND HYDROCARBON POLLUTIONS IN SELECTED TROPOSPHERIC LAYERS OF NIGER DELTA BASIN NIGERIA

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A b s t r a c t

This study analyzes spatiotemporal variations of atmospheric pollutants (CO, CH_4, SO_2, NO_2) over the Niger Delta using two years of OMI and AIRS remote sensing data, supplemented by HYSPLIT source-sink modeling. Results show CH_4 concentrations in Oguta, Warri, and Akpabuyo exceeded Port Harcourt by 30.7%, 24.9%, and 29.2%, respectively, while Port Harcourt surpassed Eket by 3.13%. SO_2 levels rose by 10.8% in Port Harcourt and 11.6% in Eket. Statistical analysis (Z-scores: 1.76–1.8; $P < 0.05$) confirmed stable temporal emission trends. CH_4 and CO dominated pollutant loads, with minimal contributions from NO_2 and SO_2. Findings implicate gas flaring from hydrocarbon activities as the primary emission source, highlighting the need for targeted mitigation policies.

Keywords: aerosol, air pollution modeling, gas flaring, environmental contaminant, HYSPLIT, remote sensing

1. INTRODUCTION

Air pollution is refers to the contamination of the atmospheric environment by chemical contaminants which may be from natural or anthropogenic sources [1], such as sulfate, nitrates, ammonia, sodium chloride, black

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carbon, and mineral dust [2,3]. others are CO, NO_2 etc. These air pollutants arise from industrial activities, biomass burning, and vehicle emissions, all of which contribute to ongoing urban pollution [1,2] and have negative consequences on health [3,4]. In the Niger Delta region of Nigeria, the impact of gas flaring on specific surface and ground waters was studied [5]. The polycyclic aromatic hydrocarbons (PAH) sources were similarly related to the flare gas as were the Fe, Zn, Cr, and Cd to gas-flaring activities. The usage of hydraulic fracturing, according to [6] has reportedly been linked to dangers to human health. Evidence reveals that the disposal of produced water compromised the fertility of the soil, groundwater, and surface water, while air contamination happened as a result of multiple hydraulic fracturing process-related activities.

Furthermore studies have shown that people's exposure to air pollution from gas flaring stations was to blame for respiratory and skin-related disorders. Both conditions caused between 21.1 and 76.3 per cent of all hospital visits; the most common ones were eye irritation and muscle pain, which put locals at risk of cardiovascular disorders [7]. In addition, there are reported cases of harvested rainwater used for drinking and domestic purposes that contained potentially toxic elements such as iron, zinc, chromium, and even lead. The toxicity was equally related to anthropogenic oil-related activities [8].

On the other hand, studies have also shown that NO_2 emission patterns within gas flaring stations in the Niger Delta of Nigeria disperse several miles to neighbouring states at concentrations of 0.029 to 0.036 mg/m^3 [9]. Moreover, there are ongoing human health risks and challenges associated with moderate to high levels of PM10 around gas-flaring communities in Bayelsa, Nigeria. The presence of heavy metal particulates increases the risk of carcinogenic disorders [10], while the spatial variation of air quality, especially suspended particulate matter in the ambient environment, can be induced by such anthropogenic activity [11]. Given these challenges, there is a need to evaluate the effects of gas flaring on tropospheric concentrations in the Niger Delta basin using time-series modeling. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model is particularly useful, as it links meteorological conditions with pollutant release, dispersion, and diffusion in the atmosphere [12]. While many studies focus on pollutant concentrations at specific times and locations [13][14], there is insufficient evidence on the use of HYSPLIT for assessing the impacts of hydrocarbon-related gas flaring on tropospheric aerosols in the region. Previous work has shown that continual gas flaring is consistent with simulated dispersion patterns [15]. Atmospheric aerosols occur mainly through the direct emission of primary aerosols into the atmosphere or through the formation of secondary aerosols as a result of chemical reactions in the atmosphere. These secondary organic aerosols, such as CO, CH_4, SO_2, and NO_2, are created in particular through the complex interaction of volatile organic compounds and sunlight, combustion of hydrocarbons and chemicals present in the air [16]. They are also associated with several health problems, such as decreased heart rate, increased asthma, and irritation of the airways [17]. Therefore, several countries have classified an air quality index (AQI) based on the five main pollutants (O_3, PM2.5 and PM10, CO, SO_2, and NO_2) for continuous monitoring of aerosol pollution [18]. There is also limited data in the proposed region concerning secondary aerosol from gas flaring and evidence of association. This study therefore, aims to conduct a spatiotemporal analysis of four major gaseous pollutants (CO, CH_4, SO_2, and NO_2) over the Niger Delta region of Nigeria. The study further investigates pollutant sources, transport trajectories, and the extent of their spatial spread within and beyond the region.

2. MATERIALS AND METHODS

2.1. Location and Description of Study Area

The Niger Delta basin is a top-tier petroleum province, is roughly located between latitudes 4°N and 6°N and longitudes 4°E and 8°E. Its area is about 75,000 km^2, and its clastic fill is 12,000 m. It is one of the world's most productive tertiary deltas for petroleum production, and collectively they make up around 5% of global oil and gas reserves. The Tertiary Niger Delta's geological expanse is part of the Niger Delta's onshore region shown in Figure 1(a-c) and is defined by southern Nigeria's geology [19]. The Benin flank, an east-northeast sloping hinge line south of the West Africa basement massif, forms the northern limit [20].

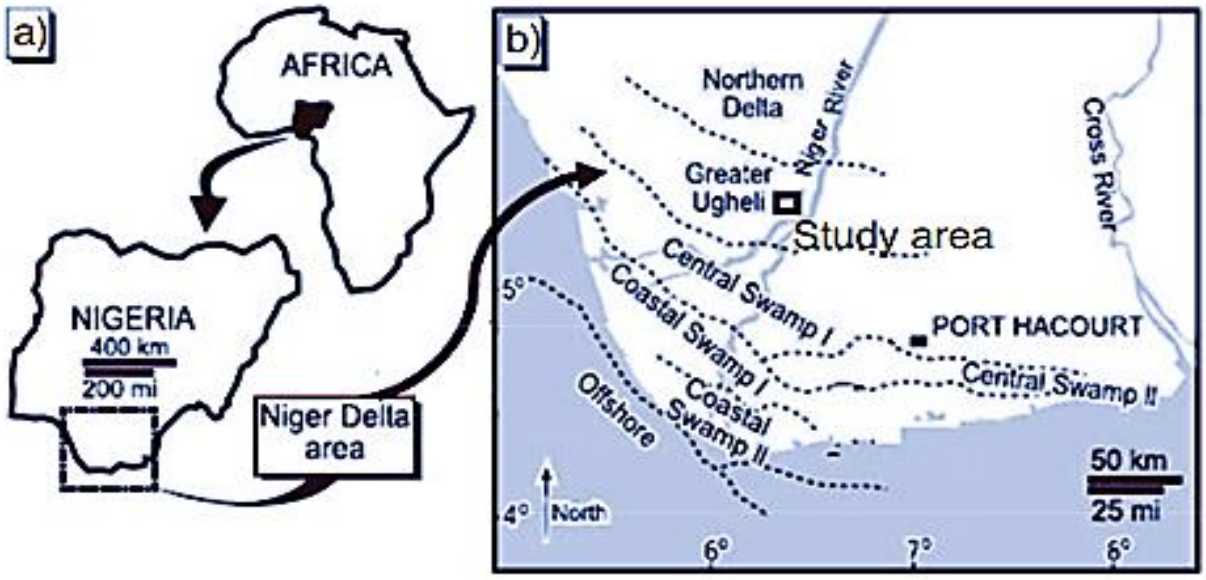

Fig. 1(a). Map of the Niger Delta basin showing the different depositional (depobelts) belts (Source: Doust and Omatsola, 1990)

Nigeria flares more natural gas connected with oil extraction than several other nations. According to the World Bank, Nigeria is among nine nations in the world with a high volume of gas flaring, with Russia leading the pack. Hence, natural gas flaring accounts for around 70% of the associated gas (AG) production, or roughly 3.5 billion cubic feet, according to annual projections. Although gas flaring is typically discouraged, harmful toxic particles, greenhouse gases, and methane are frequently discharged by flaring. Nigeria is ranked among the top 10 largest global gas flaring nations, while Russia is the number one nation. Global published data showed that the volume of emissions from Nigeria was around 425.9 billion cubic feet in 2019, while the volume from the Russian Federation was estimated to be 812 billion cubic feet annually [21, 22]. The World Bank report further stated that 357 million tonnes of CO_2 were flared in 2022, of which 315 million tonnes were CO_2 and 40 million tonnes CH_4. Subsequently, the global effort aimed at reducing gas flaring led to a reduction of flared gas by 1.3 billion cubic meters, with Nigeria leading the

effort with a 20% reduction in 2022 from the 2021 statistics from the World Bank. Consequently, 75% of the entire gas flaring in Nigeria occurs within the Niger Delta region [23], as a result of Oil exploration. Hence, this study will focus on this region. The Niger Delta accounts for approximately 7.5% of Nigeria's population and remains the most affected region by gas flaring. This study therefore focuses on five major oil-producing and industrial locations: Eket, Oguta, Akpabuyo (APK), Port Harcourt (PHC), and Warri, all of which host dense clusters of petroleum-related activities (Figure 1a–c)

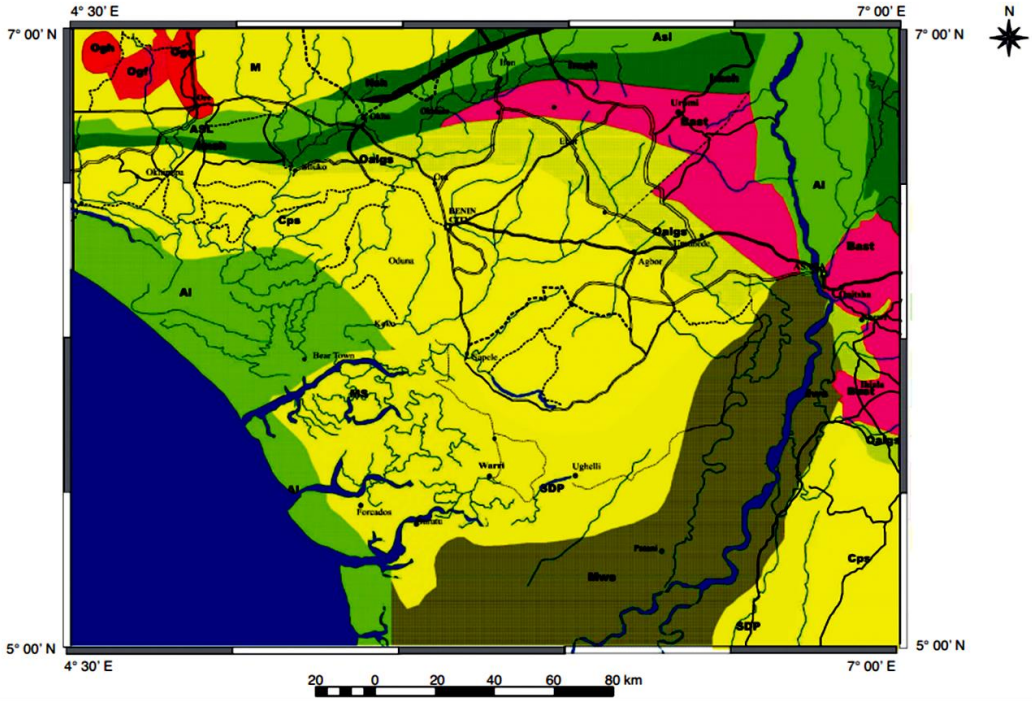

Fig. 1(b). Regional geology map of the Niger Delta basin, Nigeria (Source: Opara et al., 2013)

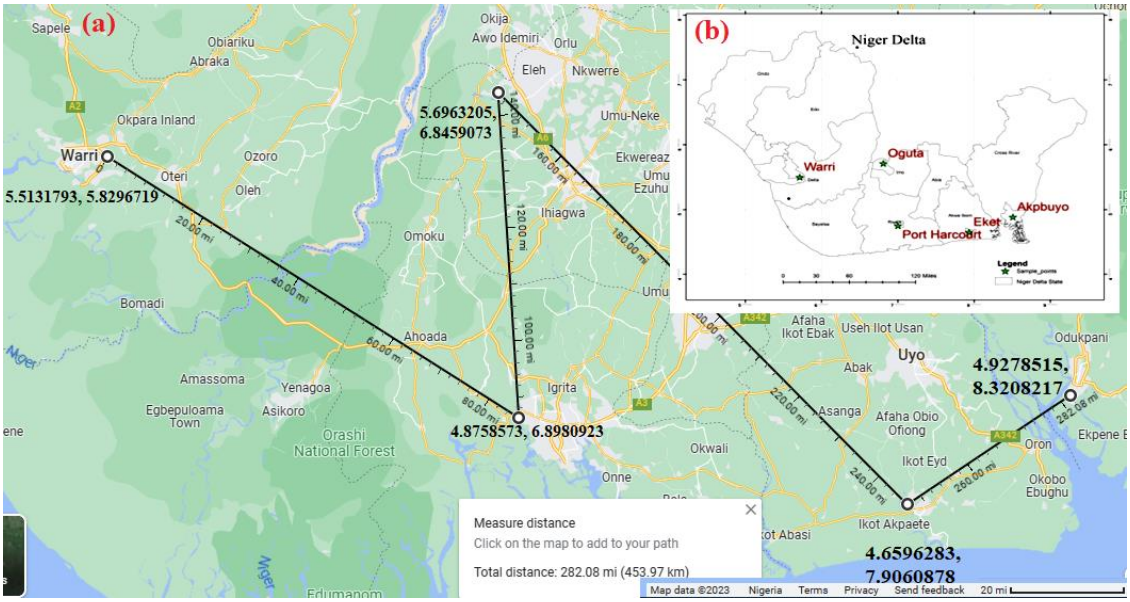

Fig. 1(c). Map of study locations showing sampling points

2.2. Ozone Monitoring Instrument (OMI)

The Ozone Monitoring Instrument (OMI) on-board NASA's Aura satellite was designed as a successor to the Tropical Ozone Measuring Mission (TOMS), especially for ozone measurements [24]. It offers measurements of SO_2, UV irradiance, erythemal UV exposure, tropospheric aerosols, and maximum reflectivity from the Earth's surface and cloud. Hence, the NO_2 and SO_2 were acquired from it at [25].

2.3. Atmospheric Infrared Sounders (AIRS)

The Atmospheric Infrared Sounder (AIRS) sensor was launched on May 4, 2002, aboard NASA's Aqua satellite. Its primary mission is to measure by mapping the air and atmospheric parameters such as temperature, water vapor, and trace greenhouse gases such as ozone, carbon monoxide, carbon dioxide, and methane [26]. Due to its strong spectral signature and minimal water vapour interference, with an estimated accuracy of 15%, it is regarded as a reliable retrieval platform.

For this study, CH_4 and CO data were obtained from AIRS through the NASA GIOVANNI platform[25] for the period 2012–2015.

2.4. NOAA Hybrid Single Particle-Lagrangian Integrated Trajectory (HYSPLIT)

The origin, method of transportation, and concentration of pollutants in the research areas were determined using the National Oceanic and Atmospheric Administration (NOAA) HYSPLIT model. The model serves as a tool to describe how potentially dangerous substances are transported, disseminated, and deposited in the atmosphere. The HYSPLIT model was used to manipulate simple air parcel trajectories towards dispersion and deposition simulations. The model is a combination of the Lagrangian approach, which employs a shifting frame of reference to calculate advection and diffusion as air parcels travel away from their initial position, and the Eulerian method, which computes pollutant air concentrations using a fixed

three-dimensional grid. The forward trajectory approach, which provided the direction, concentration, and specific site of pollutant deposition, was retained in this investigation.

3. RESULTS AND DISCUSSIONS

Figures 2.1(a-e) presents the time series plot for the various areas under investigation. Key findings from the plots indicate that CH_4 emissions peaked in December (the dry season) at all of the study locations, whereas the lowest value was observed in June (the rainy season) due to wet deposition. A comparison with rainfall (RF) shows that the peak of rainfall marks the least occurrence of all the parameters and vice versa. Subsequently, the CH_4 concentrations showed an increasing and decreasing pattern due to deposition, which is influenced by the prevailing conditions.

These increased points/days may likely translate to increased health risks and their associated effects, assuming a linear relationship between CH_4 concentration and health effects. However, there is great uncertainty as to how these relationships will develop. Furthermore, in 2015, it was observed that CH_4 emissions do not show a very distinct season variation as was observed with NO_2 and CO. This implies that wet deposition has more effect on NO_2 and CO. Another possibility may be as a result of increased CH_4 emissions starting from 2015.

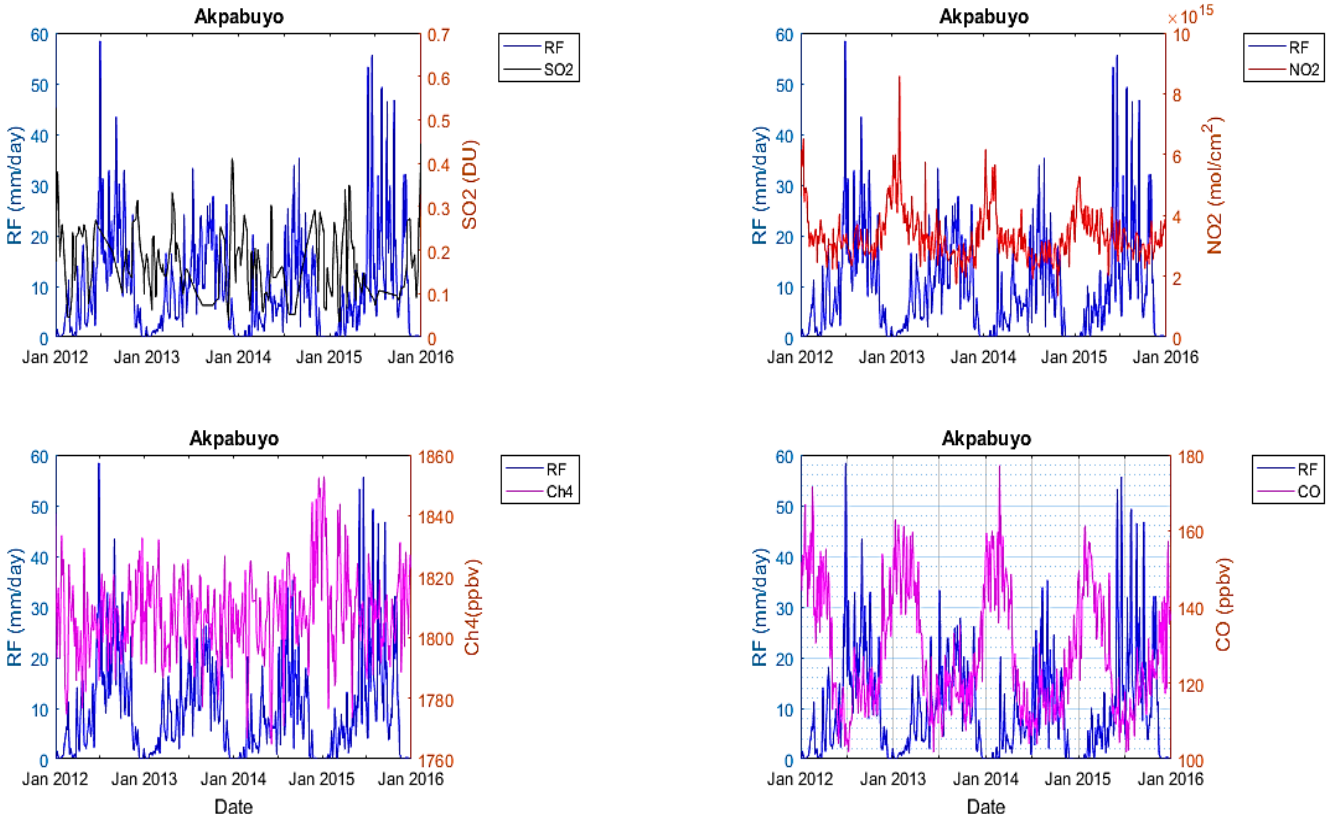

Fig. 2.1(a). Time series plot showing the particulate abundance over Akpabuyo

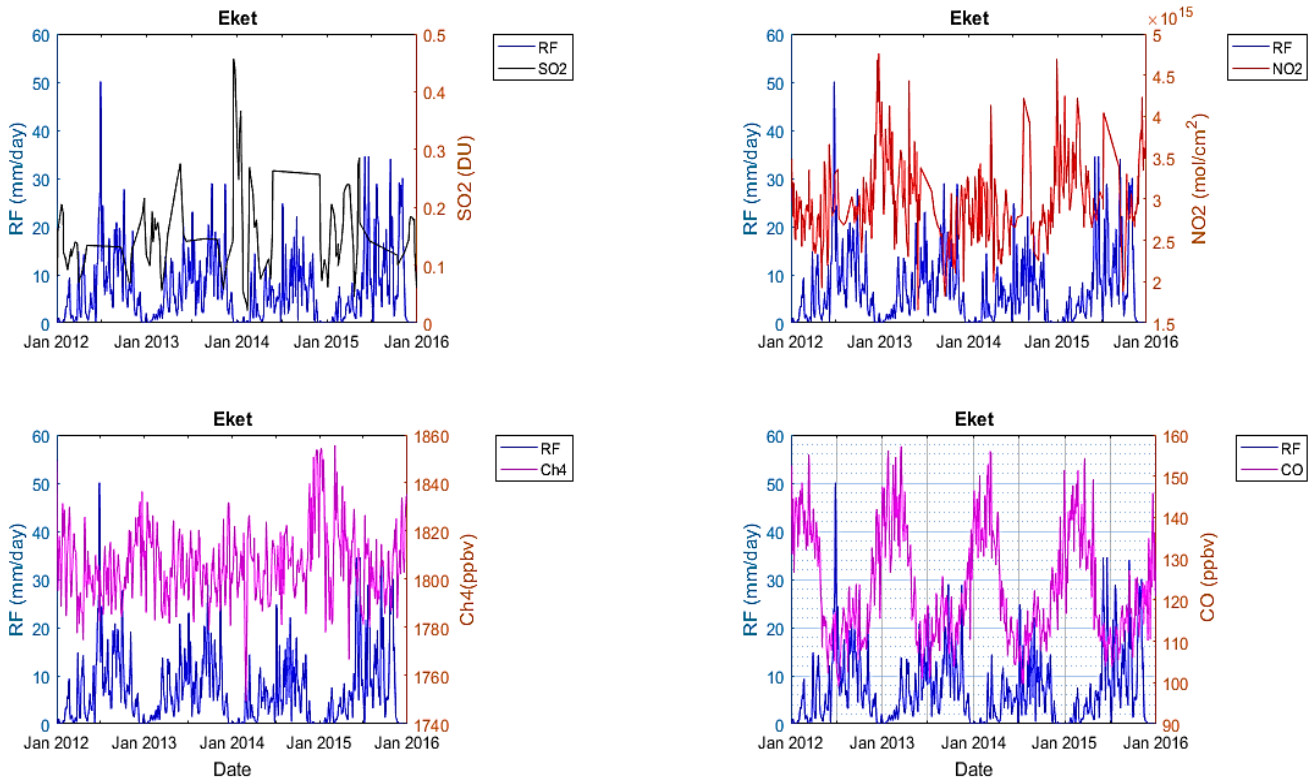

Fig. 2.1(b). Time series plot showing the particulate abundance over Eket

SO_2 concentrations peaked annually between January and March (dry season) and declined to minimum values in July before rising again in August and September. A further probe into the SO_2-RF relationship also shows that wet deposition does not apply at all times. Observation shows that there are times when both SO_2 and RF are at their peak at the same time. This scenario requires further investigation to understand the dynamics of SO_2 in the atmosphere. If established, it implies that the atmospheric effect of SO_2 may not be completely known.

Also, CO trends (curves) showed a consistent trend in each area, with emissions rising from January to April, declining until they reached their lowest point in July, and then rising once more to form another peak between August and September. According to this data, CO emission maintains a twofold maximum in Nigeria at the height of the dry season and during August, possibly at the ‘’August break’’. The August break is the period during the rainy season when the rains cease for a period of 1 or 2 weeks.

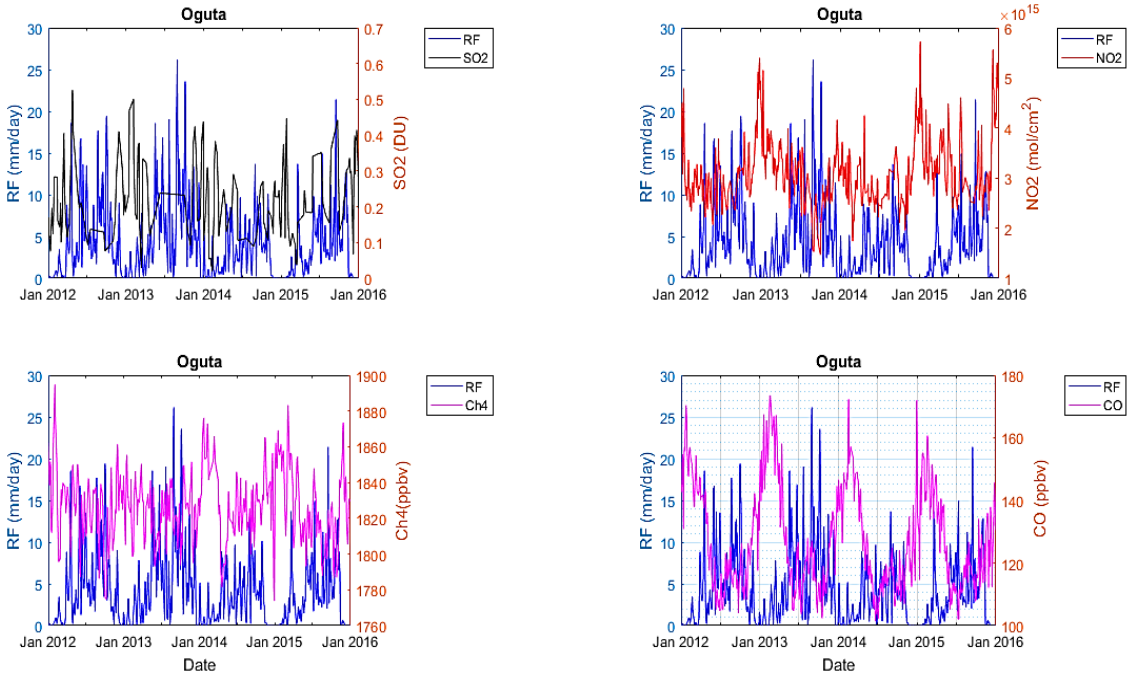

Fig. 2.1(c). Time series plot showing the particulate abundance over Oguta

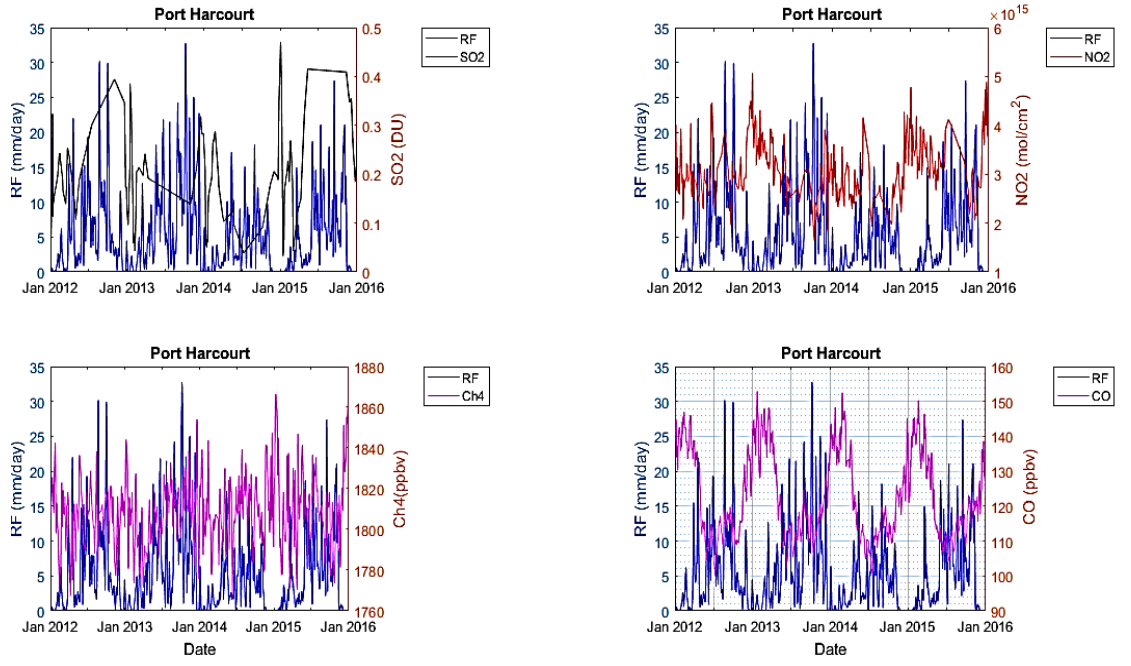

Fig. 2.1(d). Time series plot showing the particulate abundance over Port Harcourt

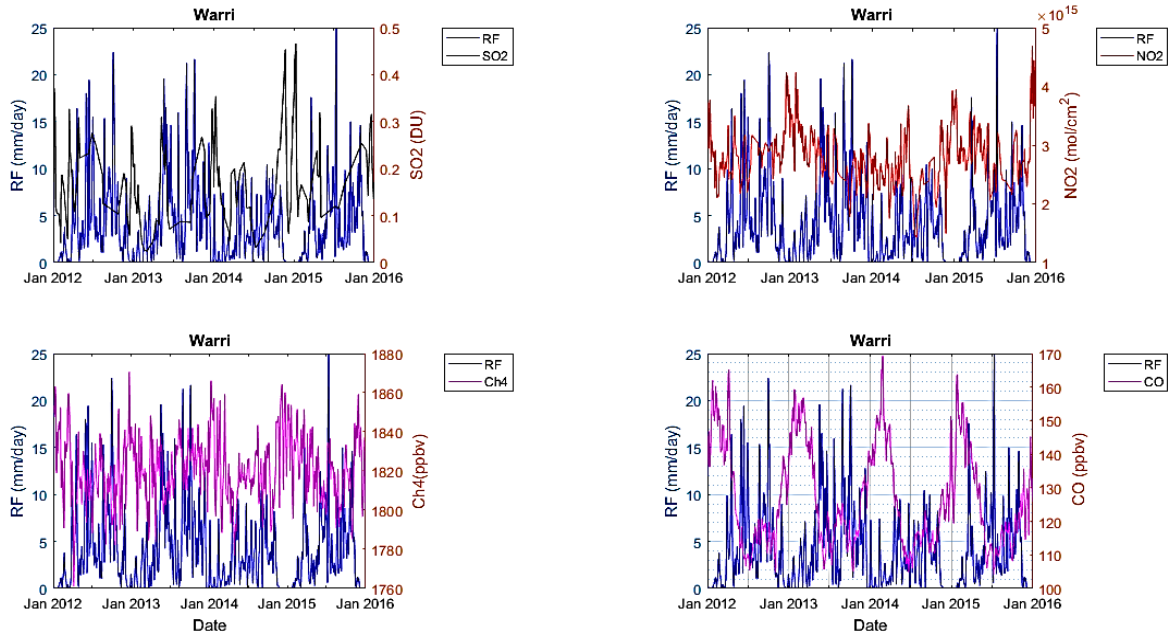

Fig. 2.1(e). Time series plot showing the particulate abundance over Warri

3.1 Annual Variation of Species

The difference observed in the mean of the individual gases for the two years was considered statistically significant when p <0.05 (Table 1a). The total annual concentration of the individual gases is shown in Table 1b with the differences between the two years [27].

Table 1a. Statistical inference from the means of the years under investigation

	Akpabuyo	**Eket**	**Oguta**	**Port Harcout**	**Warri**
	Zcal	Zcal	Zcal	Zcal	Zcal
CH_4	0.116	0.118	0.677	0.118	0.500
CO	0.432	0.134	0.653	0.983	0.885
NO_2	0.752	1.474	0.944	0.545	0.181
SO_2	0.742	1.803	0.931	1.769	0.574

The Z-test was run for emission concentrations in 2013 and 2015 with a 0.05 level of significance and a critical value of 1.96, as shown in Table 1a. The findings imply that, except for SO_2, which exhibited a substantial variation in concentration in PHC and Eket, where the Z computed was 1.76 and 1.8, respectively, the variation in emission concentrations over time is negligible in all locations. Table 1b further revealed that SO_2 increased by 10.8% and 11.6%, respectively, in PHC and Eket from the 2013 value.

Table 1b. Percentage (%) Annual variation of Atmospheric Emissions between 2013 and 2015

	% Difference by year											
	CH_4			**NO_2**			**SO_2**			**CO**		
Location	**2013**	**2015**	**% diff**	**2013**	**2015**	**% diff**	**2013**	**2015**	**% diff**	**2013**	**2015**	**% diff**
PHC	1.23×10^{21}	9.8186×10^{20}	**11.3**	-3.93×10^{31}	-4.31×10^{31}	**-4.62**	-4.69×10^{31}	-5.83×10^{31}	**-10.8**	8.79×10^{19}	9.07×10^{19}	**-1.54**
Eket	1.08×10^{21}	1.0217×10^{21}	**2.94**	-3.30×10^{31}	-4.70×10^{31}	**-17.5**	-4.83×10^{31}	-6.10×10^{31}	**-11.6**	9.24×10^{19}	9.07×10^{19}	**0.93**
Oguta	1.24×10^{21}	1.06×10^{21}	**7.83**	-2.92×10^{31}	-3.56×10^{31}	**-9.88**	-4.19×10^{31}	-4.83×10^{31}	**-7.10**	1.03×10^{20}	9.30×10^{19}	**510**
Warri	1.14×10^{21}	9.96×10^{20}	**6.74**	-3.68×10^{31}	-3.81×10^{31}	**-1.74**	-4.95×10^{31}	-5.21×10^{31}	**-2.56**	1.03×10^{20}	8.87×10^{19}	**7.45**
AKP	1.15×10^{21}	1.09×10^{21}	**2.53**	-2.79×10^{31}	-3.17×10^{31}	**-6.38**	-4.31×10^{31}	-4.69×10^{31}	**-4.22**	1.12×10^{20}	1.05×10^{20}	**3.34**

Description: PHC: Port Harcourt, AKP: Akpabuyo

According to Table 1b's reporting of the percentage fluctuation of the other atmospheric species, CH_4 and CO are the two most prevalent atmospheric gases out of the four under study.

Given the positive values recorded for the annual % difference determined for the various sites, the analysis in Table 1b's conclusion indicated that CH_4 was more plentiful in 2013 than it was in 2015. The highest CH_4 emission was noted in Oguta in 2013 (1.24×10^{21} mol/cm^2), followed by Port Harcourt (1.14×10^{21} mol/cm^2) and Eket (1.08×10^{21} mol/cm^2). However, all of the locations' CH_4 emissions decreased in 2015. It was particularly noticeable in Port Harcourt (PHC), where a fall of 11.3% was seen, followed by reductions of 7.83% in Oguta, 6.74 % in Warri, 2.94% in Eket, and 2.53% in Akpabuyo. The decreased crude oil drilling and associated activities in the Nigerian Niger Delta region in 2015 may be responsible for the decreased CH_4 emissions in all of the analysed locations. This was related to the 2015 Nigerian militant operations that obstructed petroleum-related activities, particularly gas flaring, which is a significant source of Methane emissions in the research area [28]. The particles emitted in Port Harcourt were transported to Oguta as shown by the HYSPLIT model result in Figure 3(a-d).

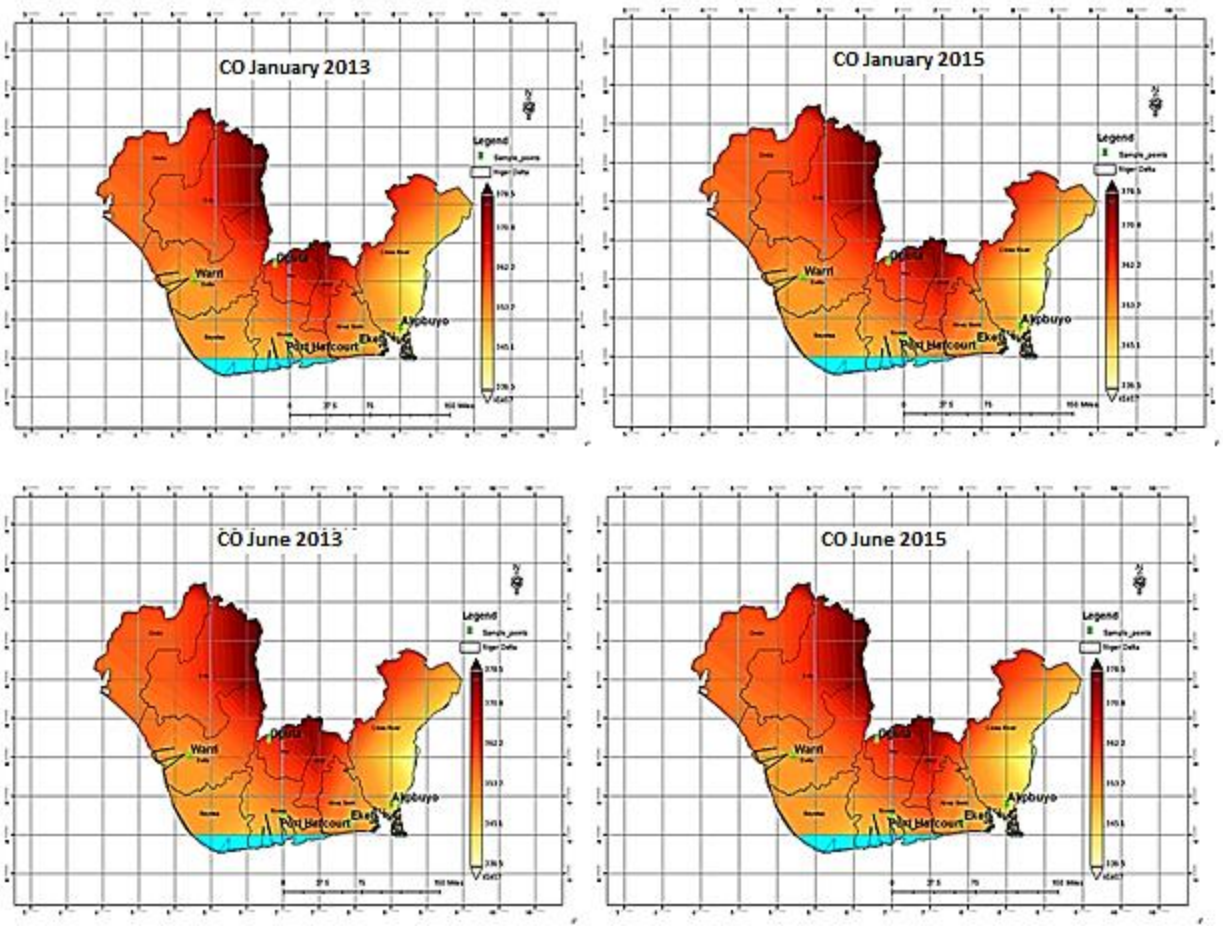

Fig. 3(a). Spatial Concentrations of CO across the study area within the period of study

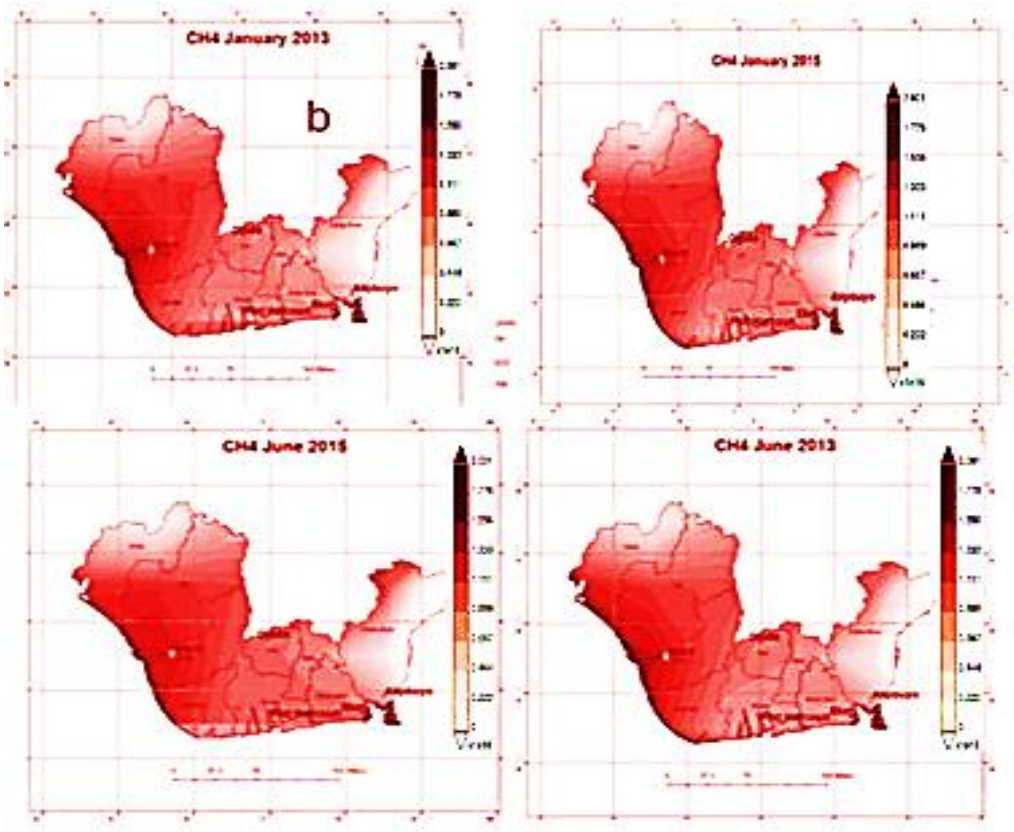

Fig. 3(b). Spatial Concentrations of CH_4 across the study area within the period of study

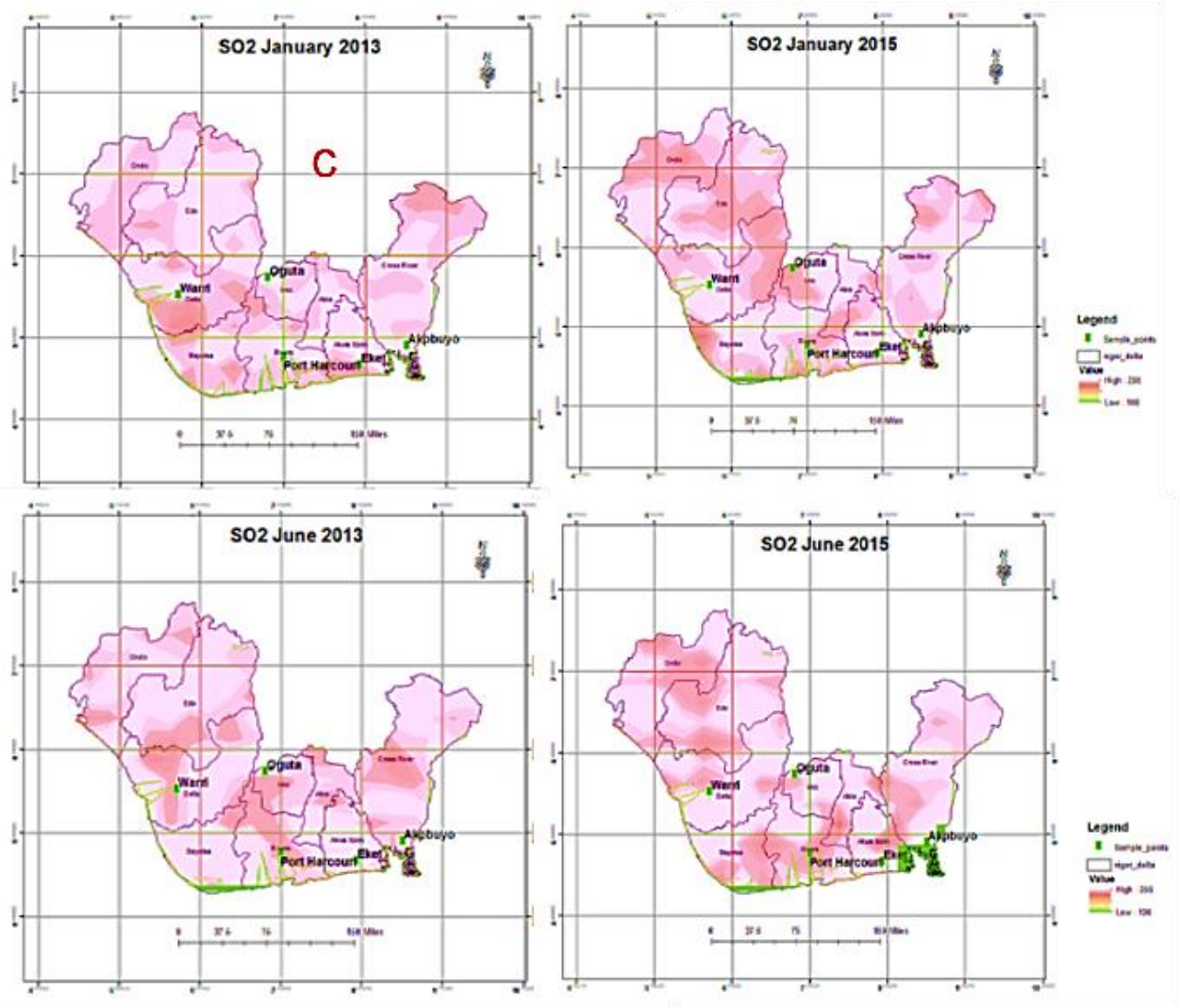

Fig. 3(c). Spatial Concentrations of SO_2 across the study area within the study period

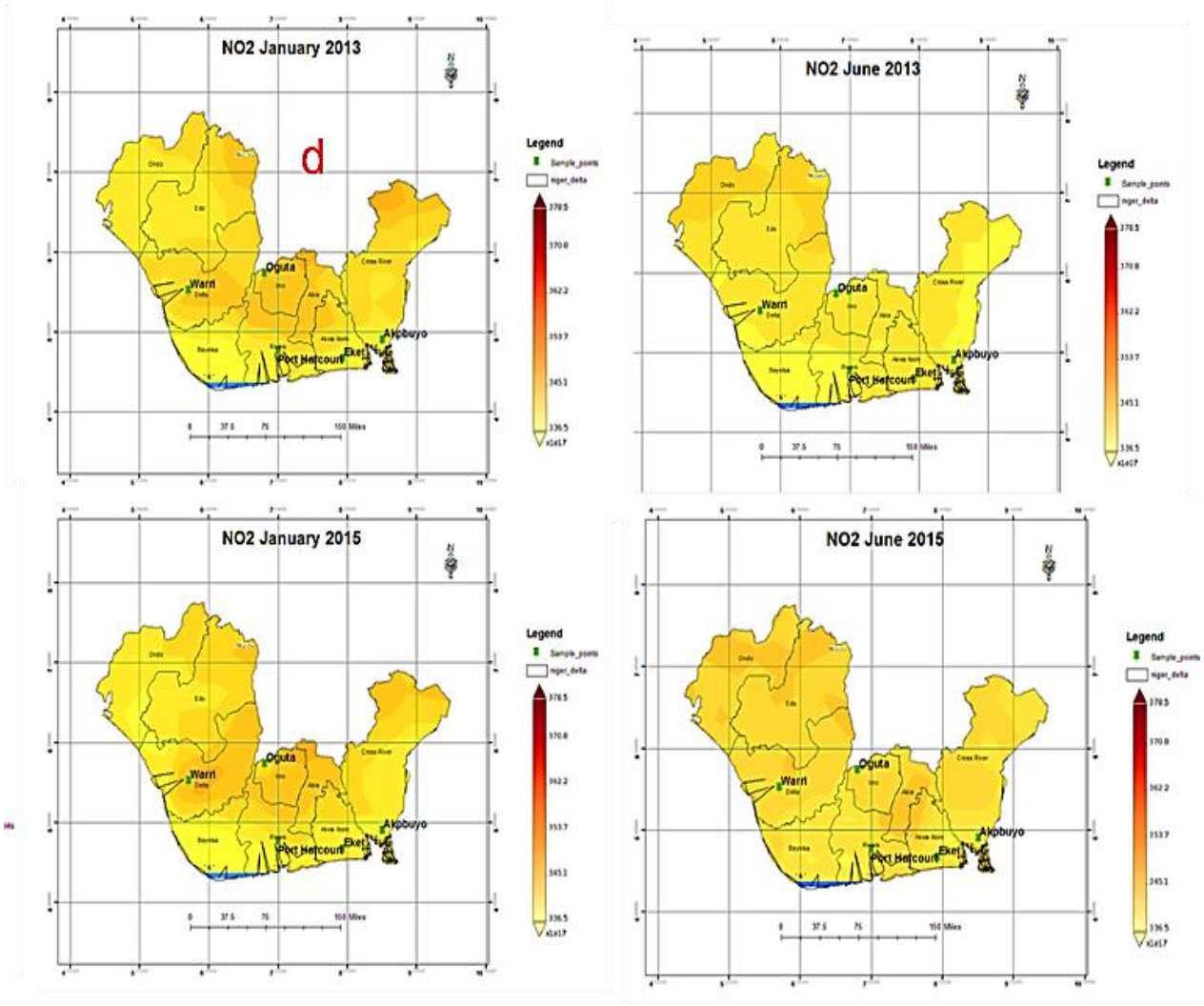

Fig. 3(d). Spatial Concentration of NO_2 across the study area within the study period

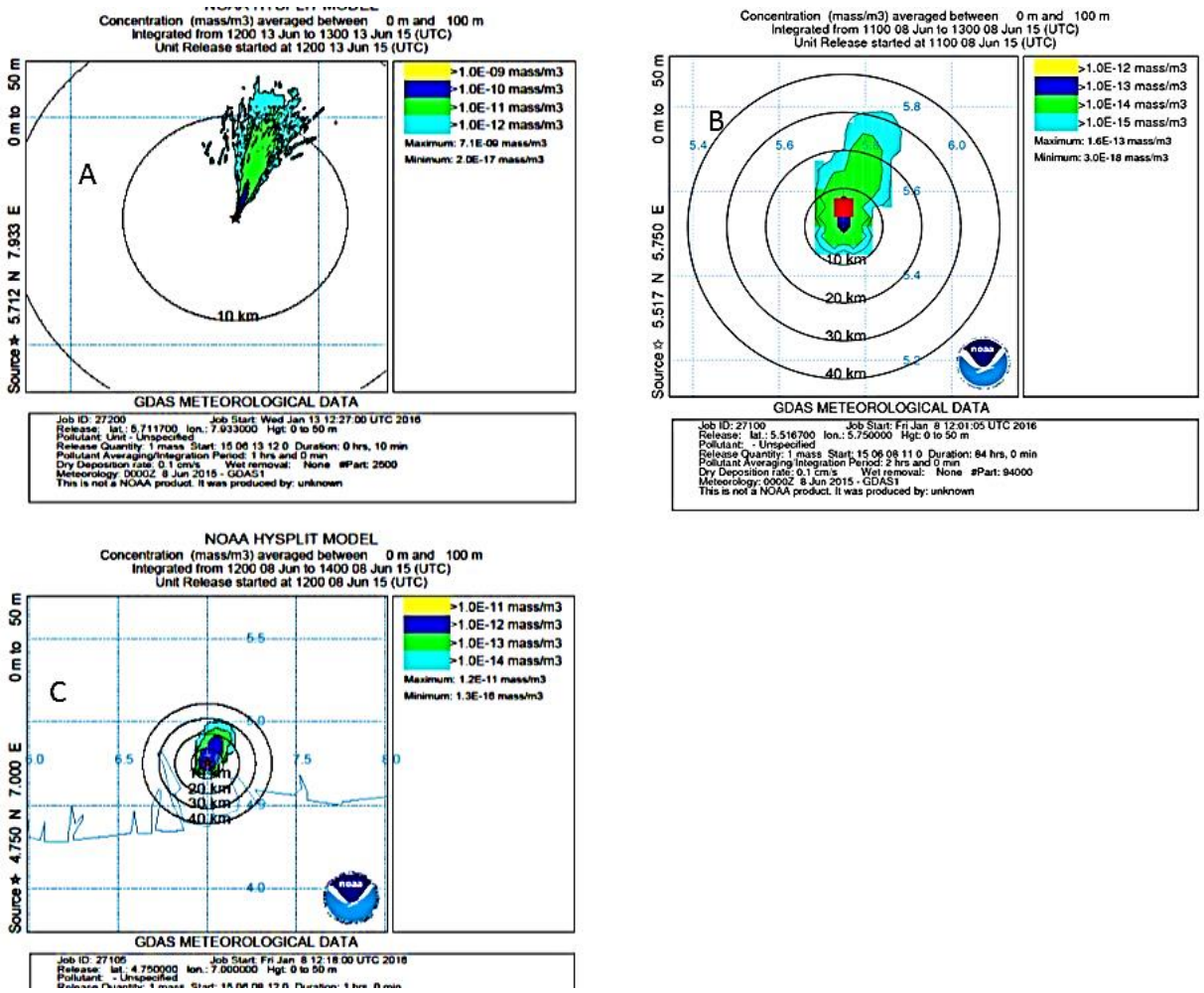

Fig. 4(a-c). HYSPLIT models at a height of 0-50 meters in parts of the study area:(a) The concentration of pollutants in Oguta (b) Hysplit concentration of pollutants in Warri (c) The concentration of pollutants in Port Harcourt

Particles are scattered towards the north of Port Harcourt, where Oguta is located, according to the models above in Figure 4(a-c). As a result, Oguta receives massive amounts of gases from Port Harcourt. Based on the evaluation of the Hysplit model for Oguta, the species does not travel far before being deposited (having a radius of influence of 10km). This suggests that pollutants are discharged near Oguta and its surroundings, where many of them are developed. The HYSPLIT model reference also demonstrated that emissions from Eket are diffused toward Akpabuyo, whereas those from Port Harcourt (PHC) and Warri are transported towards Oguta. Additionally, the models in Figure 5(a-b) demonstrated that whereas gases are spread up to a distance of 40 km in the other places, they are not dispersed beyond a distance of 10 km in Oguta and Akpabuyo, as shown in Figure 4.

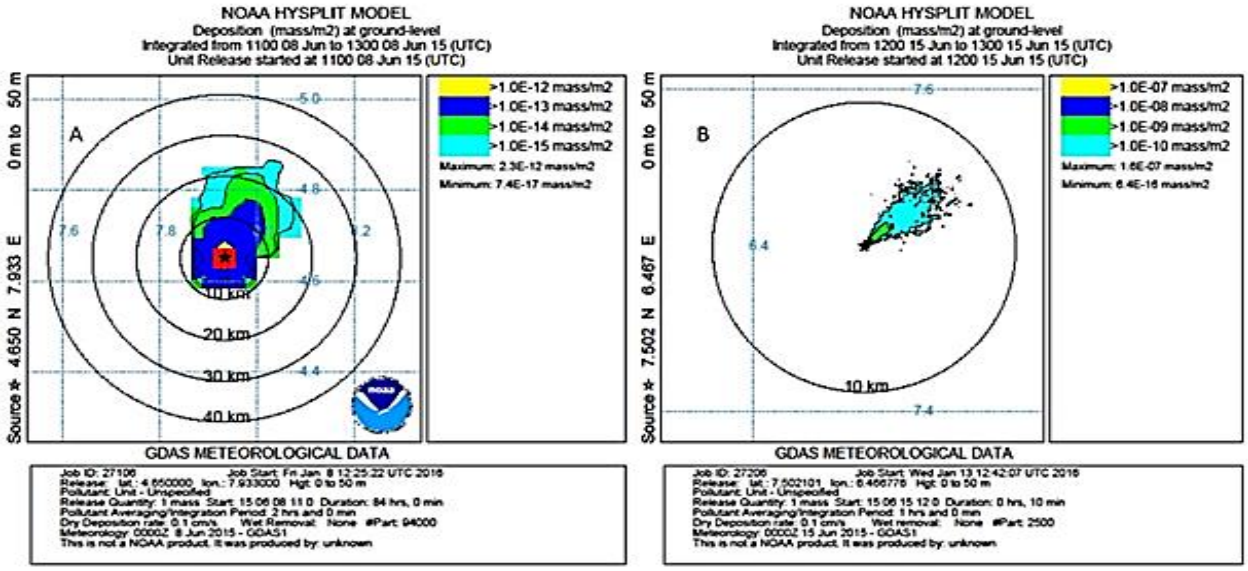

Fig. 5(a-b). HYSPLIT models at a height of 0-50 meters in parts of the study area: (a) Concentration of pollutants in Eket (b) Hysplit concentration of pollutants in Akpabuyo

Table 2a. Distance of deposition of the particle

	Deposition distance (km)	Concentration radius (km)
Port Harcourt	40km	40km
Oguta	10km	10km
Eket	40km	40km
Warri	40km	40km
Akpabuyo	10km	10km

From the analysis of the HYSPLIT models, Table 2a confirmed that the study areas have their radius of influence respectively.

3.2 The percentage Difference Observed in the Locations

The variance in species concentration in the atmosphere at each place where calculations were made is shown in Table 2b. The analysis was performed on each gas separately using [29] % difference calculation Eq (3.1).

$$\% \text{ difference} = \left(\frac{(T_{rl} - T_{ot})}{T_{rl} + T_{ot}}\right) \times 100 \quad (3.1)$$

Where $T_{rl,}$ is the total in the reference location and T_{ot}, is the total in the other location.

Table 2b. Study location variance in species concentrations

	% Difference by location					
CH_4	Port Harcourt	5.99×10^{20}	Ref Port Harcourt	Eket	Oguta	Warri
	Eket	5.63×10^{20}	3.13×10^{0}			
	Oguta	1.06×10^{21}	-3.07×10^{01}	-3.07×10^{01}		
	Warri	9.96×10^{20}	-2.49×10^{01}	-2.78×10^{01}	3.11284	
	Akpabuyo	1.09×10^{21}	-2.92×10^{01}	-3.20×10^{01}	-1.54052	-4.65×10^{0}
	in the four locations					
NO_2	Port Harcourt	-1.27×10^{31}	Ref Port Harcourt	Eket	Oguta	Warri
	Eket	-1.02×10^{31}	11.01967858			
	Oguta	-3.56×10^{31}	-50.09503934	-55.5944		
	Warri	-3.81×10^{31}	-50.06939232	-37.9104	-3.39213	
	Akpabuyo	-3.17×10^{31}	-42.86837789	-30.8596	5.587393	9.169054
SO_2	Port Harcourt	-1.65×10^{31}	Ref Port Harcourt	Eket	Oguta	Warri
	Eket	-2.03×10^{31}	-10.43639414			
	Oguta	-4.83×10^{31}	-49.12133495	-40.7753		
	Warri	-5.21×10^{31}	-51.94053065	-43.8829	-3.78486	
	Akpabuyo	-4.69×10^{31}	-47.99746726	-39.5418	1.470588	5.252525
CO	Port Harcourt	6.02×10^{19}	Ref Port Harcourt	Eket	Oguta	Warri
	Eket	5.57×10^{19}	3.927886031			
	Oguta	9.30×10^{19}	-21.39240218	-25.1093		
	Warri	8.87×10^{19}	-19.12267426	-22.8787	2.366538	
	Akpabuyo	1.05×10^{20}	-26.99293249	-30.5964	-5.94375	-8.29861

Using Port Harcourt (PHC) as a reference location, the findings indicated that the volumes of CH_4 in Oguta, Warri, and Akpabuyo were greater than those in PHC by 30.7%, 24.9%, and 29.2%, respectively, whereas the volumes in PHC are greater than those in Eket by 3.13%. When the Eket CH_4 value was compared to those from Oguta, Warri, and Akpabuyo, the results revealed that CH_4 occurred more frequently in each location at a different percentage: 30.7% in Oguta, 27.8% in Warri, and 32% in Akpabuyo using Eket as a reference location. When comparing Oguta's CH_4 concentration to that of Warri and Akpabuyo, it was found that Oguta was higher than Warri by 3.11% and greater than Akpabuyo by 1.54%. When the amount of CH_4 in Warri and Akpabuyo is compared using Warri as the reference location, the result reveals that Akpabuyo has 4.65% more CH4 than Warri, and similarly observed by [30].

3.3 Spatial Variation of the Atmospheric Pollutants

The analysis of the difference in NO_2 levels across the different study sites revealed that NO_2 levels are higher in Oguta (by 50%), Warri (by 50%), and Akpabuyo (by 42%), whereas, in Eket, the concentration is lower by 11% in comparison to Port Harcourt as a reference site. These areas exhibited higher NO_2 emissions during the study period when the value for Eket was contrasted with the values for Oguta, Warri, and Akpabuyo. Warri's NO_2 emission was found to be lower in Oguta by 3.39%, whilst Akpabuyo was higher at 5.5%. The NO_2 emission in Akpabuyo was 9.16% greater than Warri's when the concentration for Akpabuyo emission and Warri's emission was then compared. In general, the results showed that Warri, Oguta, Akpabuyo, and Port Harcourt had the greatest NO_2 emission levels, while Eket had the lowest levels. While it was noted that Warri recorded the highest value, it was followed by Oguta, Akpabuyo, Eket, and then Port Harcourt. The examination of SO_2 concentrations across the research region suggests that the emission of this gas is extremely small. Based on the CO emission variation in the study areas, Port Harcourt's CO emission was higher than Eket's CO emission by 3.92%, and Warri, Oguta, and Akpabuyo CO emissions were lower by 19.12%, 21.3%, and 26.9%, respectively. These results suggest that CH_4 and CO were the key pollutants driving air quality risks, consistent with previous studies [7, 31]. The CO emission in Eket was reduced by 25.1%, 22.8%, and 30.5% in comparison to the levels observed in Oguta, Warri, and Akpabuyo.

With this result in Oguta, Warri had 2.3% greater emissions, while Akpabuyo had 5.94% more CO concentration. Also, Akpabuyo had an 8.2% decrease in emissions over Warri. According to these analyses, CO and CH_4 are the main atmospheric gases to worry about, although SO_2 and NO_2 are infrequent. It's suggested that the flaring of gas related to hydrocarbons during the separation process was the cause of the observed increased levels of CH_4 and CO [32].

3.4 Seasonal Analysis of Atmospheric Pollutant Concentrations

The results in Tables 3 and 4 were tabulated to compare the seasonal values for the various years. In the first section (Table 3), the variation in loading for the two seasons within a single year was investigated, but in the second section (Table 4), loading for the same season based on several years was examined. According to the comparison for 2013, both PHC and Oguta had higher CH_4 emissions during the rainy season, with 2.69% and 2.83 %. The dry season concentration was higher than the rainy season value in the other areas, including Eket (3.83%), Warri (4.4%), and Akpabuyo (3.72%). According to the findings, CO loading was reduced in all of the study regions during the rainy season. According to a breakdown of the discrepancies, PHC (93.7%), Eket (93.7%), Akpabuyo (20.81%), Oguta (19.92%), and Warri (18.71%) experienced the biggest decline (Table 3a), which revealed a long term relationship with each other [33].

The seasonal fluctuations in 2015 revealed a large decrease in CH_4 emissions. According to the results, CH4 decreased during the 2015 rainy season in PHC by 15.8%, Eket by 4.36%, Oguta by 0.75%, Warri by 10.61%, and Akpabuyo by 4.32%. Additionally, all of the study sites experienced a decrease in CO emission during the 2015 rainy season, albeit to various degrees: 19.79% in PHC, 22.98% in Eket, 24% in Oguta, 27.84% in Warri, and 24.3% in Akpabuyo (Table 3b). The findings for the two years showed that in PHC and Eket, the seasonal variation of CO was more pronounced in 2013 than in 2015, indicating that there was more CO in the atmosphere during the rainy season of 2015 than in 2013. In comparison to 2013, there were lower CO emission levels during the 2015 rainy season in Oguta, Warri, and Akpabuyo. The findings in Table 3 for SO_2 and NO_2 demonstrated that during the wet season in both years, the concentration of both gases increased more than the emission values during the dry season (Table 3). Another study [34] explained that the concentrations of both pollutants were higher near major emission sources inside the stations where unconventional natural gas activities had increased.

An analysis of seasonal variation during the studied period for the same seasons but different years is shown in all of the study locations. Table 4 demonstrated that for the dry season, the total volume of CH_4

emitted in 2013 exceeded the emission in 2015 by a margin of more than 2.5 % in Port Harcourt, 2.6 % in Eket, 5.8 % in Oguta, and 2.4 % in Akpabuyo.

In Warri, the 2015 value was higher than the 2013 value by 0.6%. Additionally, the NO_2 emission results show that whereas NO_2 reduced in Eket, Oguta, Akpabuyo, and Warri by 11.11%, 10.23%, 8.96%, and 4.86% correspondingly, it increased in Port Harcourt by 8.88E-15%. According to the results, SO_2 loading increased from 2013 levels in Port Harcourt, Eket, and Warri by 13.33%, 8.57%, and 9.64%, respectively, whereas it decreased in Akpabuyo by 94.13% and stayed neutral in Oguta. Finally, the CO results showed that CO emission decreased by 6.69% in Port Harcourt, 3.43% in Oguta, 3.57% in Warri, and 2.1% in Akpabuyo, while it increased by 1.03% in Eket (Table 4). The yearly evaluation study of the atmospheric gaseous concentrations in the specified locations provided convincing evidence for both the seasonal gas relationship and the physical mechanisms of human contributions to climate variability. Based on seasonal variation observations, PHC indicates a considerable increase in CH_4 in 2013. This is consistent across all the locations and implies a significant methane release in 2013. 2015 saw a significant decline. In NO_2, on the other hand, 2015 shows a greater value than 2013, aside from Warri, with no discernible percentage difference.

It can be concluded that there is a linear link between the season and the gases during the rainy season. These findings align with previous research, which established a linear relationship between rainfall and pollutant reduction, particularly for CO and CH_4 [35].

Table 3a. Percentage (%) difference by seasons in the same year

		% Difference Dry Vs Rain										
2013	A	**CH_4**	C**H4**	**% diff D vs R**	**NO_2**	**NO_2**	**% diff D vs R**	**SO_2**	**SO_2**	**% diff D vs R**	**CO**	**CO**	**% diff D vs R**
	PHC	5.9×10^{20}	6.3×10^{20}	**-2.6×10^{0}**	-1.2×10^{31}	-2.6×10^{31}	**-3.5×10^{01}**	-1.6×10^{31}	-3.4×10^{31}	**-2.9×10^{01}**	6.0×10^{19}	1.4×10^{18}	**93.75**
	Eket	5.6×10^{20}	5.2×10^{20}	**3.8×10^{0}**	-1.0×10^{31}	-2.2×10^{31}	**-3.8×10^{01}**	-2.0×10^{31}	-2.7×10^{31}	**-1.5×10^{01}**	5.5×10^{19}	1.8×10^{18}	**93.75**
	Oguta	6.0×10^{20}	6.3×10^{20}	**-2.8×10^{0}**	-1.1×10^{31}	-1.7×10^{31}	**-2.1×10^{01}**	-1.9×10^{31}	-2.2×10^{31}	**-9.0×10^{0}**	6.2×10^{19}	4.1×10^{19}	**19.92**
	Warri	5.7×10^{20}	5.7×10^{20}	**4.4×10^{-01}**	-1.3×10^{31}	-2.4×10^{31}	**-3.1×10^{01}**	-1.8×10^{31}	-3.2×10^{31}	**-2.8×10^{01}**	6.1×10^{19}	4.2×10^{19}	**18.71**
	AKP	5.9×10^{20}	5.5×10^{20}	**3.7×10^{0}**	-1.2×10^{31}	-1.5×10^{31}	**-8.9×10^{01}**	-2.0×10^{31}	-2.3×10^{31}	**-6.2×10^{01}**	6.7×10^{19}	4.4×10^{19}	**20.82**
2015	B	**CH_4**	**CH_4**	**% diff D vs R**	**NO_2**	**NO_2**	**% diff D vs R**	**SO_2**	**SO_2**	**% diff D vs R**	**CO**	**CO**	**% diff D vs R**
	PHC	5.7×10^{20}	4.1×10^{20}	**1.6×10^{01}**	-1.3×10^{31}	-3.0×10^{31}	**-4.1×10^{01}**	-2.2×10^{31}	-3.6×10^{31}	**-2.6×10^{01}**	5.3×10^{19}	3.5×10^{19}	**19.79**
	Eket	5.3×10^{20}	4.8×10^{20}	**4.3×10^{0}**	-1.2×10^{31}	-3.4×10^{31}	**-4.5×10^{01}**	-2.4×10^{31}	-3.6×10^{31}	**-2.0×10^{01}**	5.6×10^{19}	3.5×10^{19}	**22.98**
	Oguta	5.3×10^{20}	5.2×10^{20}	**7.5×10^{-01}**	-1.4×10^{31}	-2.2×10^{31}	**-2.1×10^{01}**	-1.9×10^{31}	-2.9×10^{31}	**-2.1×10^{01}**	5.7×10^{19}	3.5×10^{19}	**24.00**
	Warri	5.8×10^{20}	4.18×10^{20}	**1.61×10^{01}**	-1.4×10^{31}	-2.4×10^{31}	**-2.6×10^{01}**	-2.1×10^{31}	-3.1×10^{31}	**-1.7×10^{01}**	5.67×10^{19}	3.20×10^{19}	**27.84**
	AKP	5.7×10^{20}	5.23×10^{20}	**4.32×10^{0}**	-1.5×10^{31}	-1.6×10^{31}	**-4.1×10^{0}**	-6.1×10^{31}	-2.7×10^{31}	**-9.57×10^{01}**	6.51×10^{19}	3.96×10^{19}	**24.30**

Description: PHC: Port Harcourt, AKP: Akpabuyo

Table 3b. Percentage (%) difference in seasonal variation for the different years

DRY												
A	**CH_4**			**NO_2**			**SO_2**			**CO**		
	2013	**2015**	**% diff**	**2013**	**2015**	**% diff**	**2013**	**2015**	**% diff**	**2013**	**2015**	**% diff**
PHC	5.9×10^{20}	5.7×10^{20}	2.5948	-1.2×10^{31}	-1.2×10^{31}	8.88×10^{-15}	-1.6×10^{31}	-2.1×10^{31}	-13.333	6.0×10^{19}	5.2×10^{19}	6.690
Eket	5.6×10^{20}	5.3×10^{20}	2.6923	-1.0×10^{31}	-1.3×10^{31}	-11.1111	-2.0×10^{31}	-2.4×10^{31}	-8.571	5.5×10^{19}	5.6×10^{19}	-1.0311
Oguta	6.0×10^{20}	5.3×10^{20}	5.892	-1.1×10^{31}	-1.4×10^{31}	-10.2362	-1.9×10^{31}	-1.9×10^{31}	0	6.2×10^{19}	5.7×10^{19}	3.4367
Warri	5.7×10^{20}	5.8×10^{20}	-0.6092	-1.2×10^{31}	-1.4×10^{31}	-4.8689	-1.7×10^{31}	-2.2×10^{31}	-9.6446	6.1×10^{19}	5.6×10^{19}	3.571
AKP	5.9×10^{20}	5.7×10^{20}	2.4639	-1.2×10^{31}	-1.5×10^{31}	-8.9605	-2.0×10^{31}	-6.1×10^{29}	94.137	6.8×10^{19}	6.5×10^{19}	2.100
Rain												
B	**CH_4**			**NO_2**			**SO_2**			**CO**		
	2013	**2015**	**% diff**	**2013**	**2015**	**% diff**	**2013**	**2015**	**% diff**	**2013**	**2015**	**% diff**
PHC	6.3×10^{20}	4.1×10^{20}	20.9	-2.66×10^{31}	-3.0×10^{31}	-6.67	-3.0×10^{31}	-3.6×10^{31}	-9.43	4.1×10^{19}	3.5×10^{19}	7.3
Eket	5.2×10^{20}	4.9×10^{20}	3.22	-2.29×10^{31}	-3.4×10^{31}	-20	-2.8×10^{31}	-3.6×10^{31}	-13.7	3.9×10^{19}	3.5×10^{19}	4.5
Oguta	6.4×10^{20}	5.3×10^{20}	9.45	-1.78×10^{31}	-2.1×10^{31}	-9.6	-2.3×10^{31}	-2.9×10^{31}	-12.1	4.1×10^{19}	3.5×10^{19}	7.7
Warri	5.6×10^{20}	4.2×10^{20}	15.0	-2.41×10^{31}	-2.4×10^{31}	0.0	-3.2×10^{31}	-3.1×10^{31}	2.09	4.2×10^{19}	3.2×10^{19}	13.1
AKP	5.5×10^{20}	5.2×10^{20}	3.06	-1.52×10^{31}	-1.6×10^{31}	-4.1	-2.3×10^{31}	-2.8×10^{31}	-9.63	4.4×10^{19}	3.9×10^{19}	5.7

Table 4. Percentage in seasonal variation for the different years

DRY												
A	**CH_4**			**NO_2**			**SO_2**			**CO**		
	2013	2015	% diff	2013	2015	% diff	2013	2015	% diff	2013	2015	% diff
PHC	5.9 x 10^{20}	5.6 x 10^{20}	2.5948	-1.2 x 10^{31}	-1.2 x 10^{31}	8.88E-15	-1.6 x 10^{31}	-2.1 x 10^{31}	-13.3333	6.0 x 10^{19}	5.2 x 10^{19}	6.6900
Eket	5.6 x 10^{20}	5.3 x 10^{20}	2.6923	-1.0 x 10^{31}	-1.2 x 10^{31}	-11.1111	-2.0 x 10^{31}	-2.4 x 10^{31}	-8.5714	5.5 x 10^{19}	5.6 x 10^{19}	-1.0311
Oguta	6.0 x 10^{20}	5.3 x 10^{20}	5.8927	-1.1 x 10^{31}	-1.4 x 10^{31}	-10.2362	-1.9 x 10^{31}	-1.9 x 10^{31}	0	6.1 x 10^{19}	5.7 x 10^{19}	3.4367
Warri	5.7 x 10^{20}	5.7 x 10^{20}	-0.6092	-1.3 x 10^{31}	-1.4 x 10^{31}	-4.8689	-1.8 x 10^{31}	-2.2 x 10^{31}	-9.6446	6.0 x 10^{19}	5.6 x 10^{19}	3.5714
AkP	5.9 x 10^{20}	5.7 x 10^{20}	2.4639	-1.2 x 10^{31}	-1.5 x 10^{31}	-8.9605	-2.0 x 10^{31}	-6.1 x 10^{29}	94.1376	6.7 x 10^{19}	6.5 x 10^{19}	2.1004
Rain												
B	**CH_4**			**NO_2**			**SO_2**			**CO**		
	2013	2015	% diff	2013	2015	% diff	2013	2015	% diff	2013	2015	% diff
PHC	6.3 x 10^{20}	4.1 x 10^{20}	20.9	-2.6 x 10^{31}	-3.0 x 10^{31}	-6.67	-3.0 x 10^{31}	-3.6 x 10^{31}	-9.43	4.0 x 10^{19}	3.5 x 10^{19}	7.3
Eket	5.2 x 10^{20}	4.9 x 10^{20}	3.22	-2.3 x 10^{31}	-3.4 x 10^{31}	-20.0	-2.7 x 10^{31}	-3.6 x 10^{31}	-13.7	3.9 x 10^{19}	3.5 x 10^{19}	4.5
Oguta	6.3 x 10^{20}	5.3 x 10^{20}	9.45	-1.7 x 10^{31}	-2.1 x 10^{31}	-9.6	-2.2 x 10^{31}	-2.9 x 10^{31}	-12.1	4.1 x 10^{19}	3.5 x 10^{19}	7.7
Warri	5.6 x 10^{20}	4.1 x 10^{20}	15.0	-2.4 x 10^{31}	-2.4 x 10^{31}	0.00	-3.1 x 10^{31}	-3.0 x 10^{31}	2.09	4.2 x 10^{19}	3.2 x 10^{19}	13.1
AKP	5.5 x 10^{20}	5.2 x 10^{20}	3.06	-1.5 x 10^{31}	-1.6 x 10^{31}	-4.1	-2.3 x 10^{31}	-2.8 x 10^{31}	-9.63	4.4 x 10^{19}	3.9 x 10^{19}	5.7

Description: PHC: Port Harcourt, AKP: Akpabuyo

4. CONCLUSION AND RECOMMENDATIONS

A detailed study was undertaken to analyse and simulate the behaviour of tropospheric aerosols in the SO_2, CH_4, CO, and NO_2 environments of the Niger Delta. The study took two years, between January 2013 and June 2015. The present study also showed that CH_4 levels of Oguta, Warri, and Akpabuyo were higher than that of Port Harcourt by 30.7, 24.9, and 29.2 percent respectively and similarly Port Harcourt's CH_4 levels were higher than that of Eket by 3.13 percent. Seasonal variation revealed that CH_4 and CO levels lowered down in the wet season in all the study sites. However, NO_2 and SO_2 concentrations rose in all the areas under study except for Warri where NO_2 was static and SO_2 reduced by 2.09%. The time series analysis was used in the study of these atmospheric pollutants with respect to time to establish the relationship between them and time and also for forecasting the trends in aerosols. Choropleth maps were used to display spatial variations in the concentration of pollutants and areas with high concentrations. The HYSPLIT model gave forward trajectories of the direction, concentration, and deposition of pollutants at 0m, 50m, and 100m AGL.

This study revealed that the level of emissions reduction in Port Harcourt has a direct impact on Oguta since pollutants from Port Harcourt spread in the north direction of Oguta. The HYSPLIT analysis showed that for Oguta most of the contaminants were deposited within 10 km, suggesting local sources. Also, the model distinguished that emissions from Port Harcourt and Warri were directed to Oguta, and emissions from Eket were dispersed to Akpabuyo. While pollutants in other sites extend up to 40 km away from the source, the dispersal in Oguta and Akpabuyo sites was within 10 km range, probably because of their low altitude which promotes pollutant accumulation. To ensure protection of the environment and the health of the people, the study suggests that proper policies on environment as well as international mechanisms that check on gas flaring in the Niger Delta region should be adopted.

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