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Dispersion modeling of PM_{10} from selected flow stations in the Niger Delta, Nigeria: implications on soot pollution

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Abstract

Background: Gas flaring in the Niger Delta releases particles which are dispersed over a wide area and have impacts on the environment and human health. The study aimed at assessing the extent of dispersion of PM_{10} emitted from gas flares in flow stations. Eight selected flow stations in Rivers and Bayelsa states were investigated. The concentrations of PM_{10} emitted from the flare stacks were monitored 60 m away from the flare stack using a hand-held Met One AEROCET 531 combined Mass Profiler and Particle Counter. Meteorological parameters such as wind speed, ambient temperature and relative humidity were monitored during the sampling campaign. PM_{10} and meteorological data were analysed for simple and descriptive statistics using SPSS for Windows (version 21.0). Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) was adopted to predict the dispersion of PM_{10} from the flow stations.

Results: Results revealed the range concentrations of PM_{10} from the flow stations (FS 1–8) as 19.9 µg/m^3 at FS 1 to 55.4 µg/m^3 at FS 8. The maximum concentration of PM_{10} at FS 8 was higher than the World Health organisation limit of 50 µg/m^3. The dispersion of PM_{10} emitted from FS 1, 4 and 7 in April 2017, had a fitting spread over Port Harcourt City.

Conclusions: The modeling results revealed dispersion of PM_{10} from the flow stations to 14 states in Nigeria. This suggests possible detrimental health and environmental effects of PM_{10} on residents in the identified states.

Keywords: Dispersion modeling, Flare stacks, Gas flaring, Meteorological parameters, Air pollution

Background

The Niger delta region of Nigeria is known to have abundance of crude oil that is found in reservoirs, which also contain natural gas referred to as associated petroleum gas (APG) separated from the crude oil at a Flow Station. During the separation, some APGs is liquefied and sent to the Nigerian Liquefied Natural Gas Company (NLNG). The remaining APG is usually disposed of by flaring (Talebi et al. 2014; Fawole et al. 2016; Ismail and Umukoro 2016). Flaring process involves the rapid oxidation of APG that releases heat, gaseous and particulate pollutants into the atmosphere. The concentrations of these pollutants depend on the amount and composition of the APG, the combustion characteristics, the flare geometry and design (Torres et al. 2012; Fawole et al. 2016). The most frequent type of flaring in the Niger Delta is the production flaring. This kind of flaring is continuous as long as crude oil is exploited (Johnson and Coderre 2011).

Particulate matter emitted from gas flares are largely black carbon, which is referred to as soot (Ana et al. 2012; USEPA 2012; Johnson et al. 2013; Fawole et al. 2016). Soot is removed by dry and wet deposition thus making it short-lived in the atmosphere. Nevertheless, it contributes to global warming and consequently, climate change

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(IPCC 2007). This is made possible in light of its ability to absorb incoming solar radiation (Ramana et al. 2010). It also influences the cloud forming process and accounts for the reduction in the surface albedo of ice and snow causing them to melt rapidly (IPCC 2007). PM_{10} is harmful especially when combined with toxic trace elements such as Cd, As, Cr, Mn, Pb, Ni, Cu, and Zn (Taiwo et al. 2014). The other air pollutants such as NO_2 and SO_2 that are associated with gas flaring are equally harmful. PM_{10} is germane to human health because it can enter into the respiratory tracts in humans, causing respiratory and cardiovascular diseases (Oguntoke et al. 2012).

The dispersion of PM_{10} is aided by meteorological conditions such as wind speed, wind direction, temperature and relative humidity. The pervasive dispersion of soot generated from gas flaring and other industrial activities in the Niger Delta coupled with its several effects on the Earth's climate and human health make the study of PM_{10} emission and dispersion pertinent.

Materials and methods

Description of study area

Rivers and Bayelsa states are the second and fourth major oil producing states in Nigeria, contributing to over 40% of the daily oil production in the country (SPDC 2006). Their land masses are 21,850 km^2 and 9059 km^2, respectively (SPDC 2006). They are situated in eastern part of the Niger Delta region and are delineated by 4°45′N 6°50′E and 4°45′N 6°05′E, respectively (Fig. 1). They have humid tropical climate profoundly influenced by their nearness to the Atlantic Ocean. The study areas characterised by two seasons in a year namely: dry and wet seasons. The dry season runs from November to March, and the wet season from April to October. The annual rainfall is about 2500 mm (SPDC 2006). The rain falls throughout the year with peaks in June and September, and a short break of low rainfall in August. The relative humidity is usually above 85% in the rainy season, and may decrease to 45.5% in the dry season (SPDC 2006). The ambient air temperature ranges between 24.5 and 32 °C in the wet season and 25 to 36 °C in the dry season (SPDC 2006). South-westerly winds are prevalent in the study areas in the rainy season, and wind speeds ranges from 0.3 to 4.5 m/s. In the dry season, wind speed of 0.3–3.5 m/s is relatively slower (SPDC 2006).

Sampling procedure

The fourth quarter in 2016 heralded the onset of soot pollution in Port Harcourt, Rivers state. In bid to identify the likely source and direction of the soot, the months of March and April 2017 were selected for this study. March signals the end of the dry season, while April ushers in the wet season.

Since the main aim of this study was to unravel the soot crises in Port Harcourt; gas flaring stations in Rivers and Bayelsa states were chosen for this study. Restricted access was granted for sampling in these selected gas flaring stations. Bayelsa state lies in the south west direction

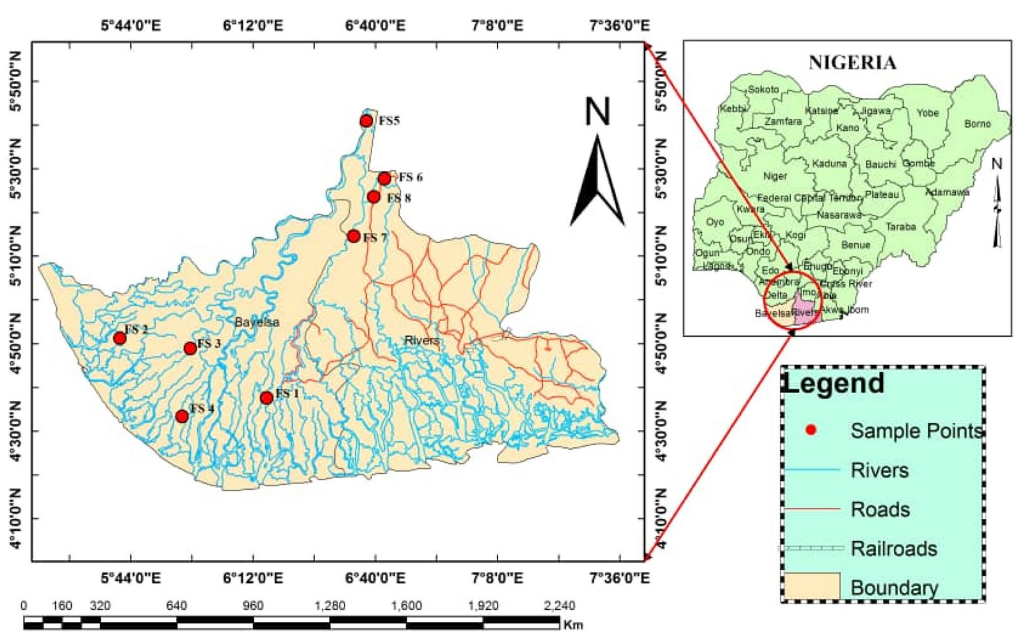


Fig. 1 Map of Nigeria showing the sampling locations

of Rivers state and pollutants emanating from this state could travel along the prevailing wind direction to Rivers state (Nwosisi et al. 2019). Gas flares in four flow stations (FS) were selected from each state during the study. The stations denoted by FS 1–4 were located in Bayelsa state, while the FS 5–8 were sited in Rivers state. The gas flare stacks were generally self and guy wire supported elevated stacks of about 31 m in height. These flares emit associated petroleum gases for 24 h a day and 365 days a year. In cases where the gas flaring stations are under maintenance, no flaring activity takes place. However, this only happens few times a year (Fig. 2).

Measurements of PM_{10} were obtained on a weekly basis in March and April 2017. Sampling was carried out at 60 m away from the flare stacks along the direction of the prevailing wind, at the various flow stations. This distance is the closest that an individual can get to the flare stack as prescribed by the Department of Petroleum Resources (DPR). DPR is a regulatory agency in Nigeria.

PM_{10} equipment/measurement

PM_{10} was measured in the windward direction of the sampling point using a hand-held Met One AEROCET 531 combined Mass Profiler and Particle Counter. This equipment when used as a particulate counter provides visual real time count information in two channels and displays on the LCD screen. When the equipment is used in mass profiling of particulates, it provides the particulate mass concentration per cubic foot of sampled air. The equipment is configured to use the stored particle count data and an algorithm to derive the mass concentration. This algorithm is proprietary and the user is not privy to it. A long life laser diode, an efficient light collecting elliptical mirror and unique optics are incorporated into the sensor to provide a high concentration limit.

PM_{10} samples were monitored using this equipment in the mass profiler mode. The isokinetic probe which functions to reduce the count errors as a result of sample flow velocity and the aerodynamics of small particles, was facing upward during the sampling. The accuracy, sensitivity, flow rate and operating temperature of the equipment were $\pm 10\%$, 0.5 µm, 0.1 cfm and 0° to +50 °C respectively. In order to ensure accurate and reliable readings, the measurements were taken at a height of two metres from ground level to provide concentration values of PM_{10} at a level at which humans are most likely exposed, while at the same time, preventing interference of fugitive dust from loose soil surfaces with the PM_{10} readings. The equipment was calibrated based on the manufacturer's recommendation before and after each batch of sampling and also, back-up batteries was at hand.

Meteorological data

The meteorological data including wind speed, wind direction, ambient temperature and relative humidity were collected using Wind Mate (WM 350), manufactured by Weatherhawk.

Statistical analysis of PM_{10}

PM_{10} data were subjected to descriptive and inferential statistics using IBM Corporation's SPSS for Windows (version 21.0). Correlation analysis was employed to determine the level of association (co-occurrence) between PM_{10} and meteorological parameters.

Fig. 2 A typical gas faring stack in the study area

Regression analysis was used to assess meteorological parameters as a factor of variation in the levels of sampled PM_{10} concentrations. The meteorological parameters served as the predictor variable (X), while the concentration of PM_{10} was the dependent variable (Y).

Dispersion modeling

The dispersion from each of the flow stations was predicted using Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) (Stein et al. 2015). This model was used to compute the likely route that particles can travel from each of the flow stations. HYSPLIT was also utilised to compute the dispersion and concentration of PM_{10} at the receptor sites. The data inputted into the model included: the type of material released from the stacks, geographical location of the flare stacks, the height of flare stack, the mass concentration of PM_{10} and the duration of the emission. The NOAA Global Assimilation System (GDAS) was used as input for the meteorological conditions of the sampling area.

Results and discussion

Meteorological parameters

Figure 3 shows the time series results of wind speed, relative humidity and temperature, observed during the sampling campaign. Whereas, the direction of the wind across the sampling areas is shown in Fig. 4. The wind speed ranged from 1.0 to 2.0 m/s at the flow stations (FS 1–8). The relative humidity varied between 56.9 and 91.4%, while temperature ranged 26.9–33.9 °C. The wind direction was predominantly in the south-easterly. The wind speed in the flow stations was fairly stable and belongs to the class F, according to the Pasquill stability class. The speed of the wind is a very critical factor in the dispersion of pollutants. The low relative humidity values were measured in the dry season, while in the wet season, higher values were observed. The temperature differences in both seasons accounts for this trend. A higher temperature, which is sometimes indicative of dry season, causes a reduction in relative humidity. The high temperature obtained could be attributed to reduction in the moisture content of the air around the stations. This could be a result of the heat from the gas flares and also the prevalence of North-East trade winds, which are usually dry, cold and dust laden (Gobo et al. 2012). All of these meteorological parameters could cumulatively, influence PM_{10} concentration and distribution.

PM_{10} concentration

The concentrations of PM_{10} at the flow stations are presented in Table 1. At FS 1 and 2, the highest concentrations of PM_{10} were observed in the second week of March (45.9 and 44.0 μg/m^3). The first (49.9 μg/m^3) and second (40.3 μg/m^3) week of March recorded the highest concentration of PM_{10} in FS 3 and 4 respectively. Likewise, in FS 5 and 6, the peak of PM_{10} concentration was in the fourth week of March (49.9 and 56.3 μg/m^3). The highest concentration at FS 7 was 47.1 μg/m^3, while in FS 8 was 55.4 μg/m^3.

The highest concentrations in FS 6 and 8 were greater than the WHO permissible limit of 50 μg/m^3 (WHO 2005). Cumulatively, FS 8 had the largest (40.7 μg/m^3) contribution of PM_{10} from gas flare into the atmosphere, while FS 1 accounted for the least (31.3 μg/m^3).

Correlation between meteorological parameters and PM_{10} concentration

The Pearson's correlation coefficients between PM_{10} and wind speed, relative humidity and temperature, at 0.05 significance level are highlighted in Table 2. Generally, there were negative correlations (R = − 0.031 to − 0.704) between PM_{10} and wind speed across the flow stations. The only positive correlation was observed at FS 4. Similarly, there was largely an inverse relationship (R = − 0.033 to − 0.677) between relative humidity and PM_{10}. FS 2 has a linear relationship (R = 0.037) between both parameters. Temperature on the other hand, showed positive relationship (R = 0.056–0.598) with PM_{10} and a negative correlation (R = − 0.100) at FS 2.

The largely negative correlation between wind speed and PM_{10} indicates that particle concentrations and dispersions at the sampling sites were more influenced by the prevailing wind speed. The wind speed in the Niger Delta is usually stable and of the class F (Edokpa and Nwagbara 2017). Akin to wind speed, relative humidity correlated negatively with PM_{10}. This implies that the higher the moisture levels in the surrounding air, the lesser the amount of particulates. This is a result of the particles absorbing moisture and becoming heavier, thus more likely to be deposited faster than the lighter fractions (Hernandez et al. 2017). Generally, as the ambient temperature increases, the particulates get easily dispersed thereby reducing its ground level concentration (Jacobson, 2005). However, in this study only one sampling area (FS 2) followed this trend. The deviation from this trend could be as a result of the plume from the flare stack being denser than the ambient temperature. Consequently instead of rising, the plume sinks thereby increasing the ground concentration of PM_{10} in such sampling sites.

Weak correlation largely existed between the meteorological conditions and PM_{10}. The relatively constant meteorological conditions in the sampling sites could be responsible.

Table 3 presents the influence of meteorological parameters on the concentrations of PM_{10}. The regression

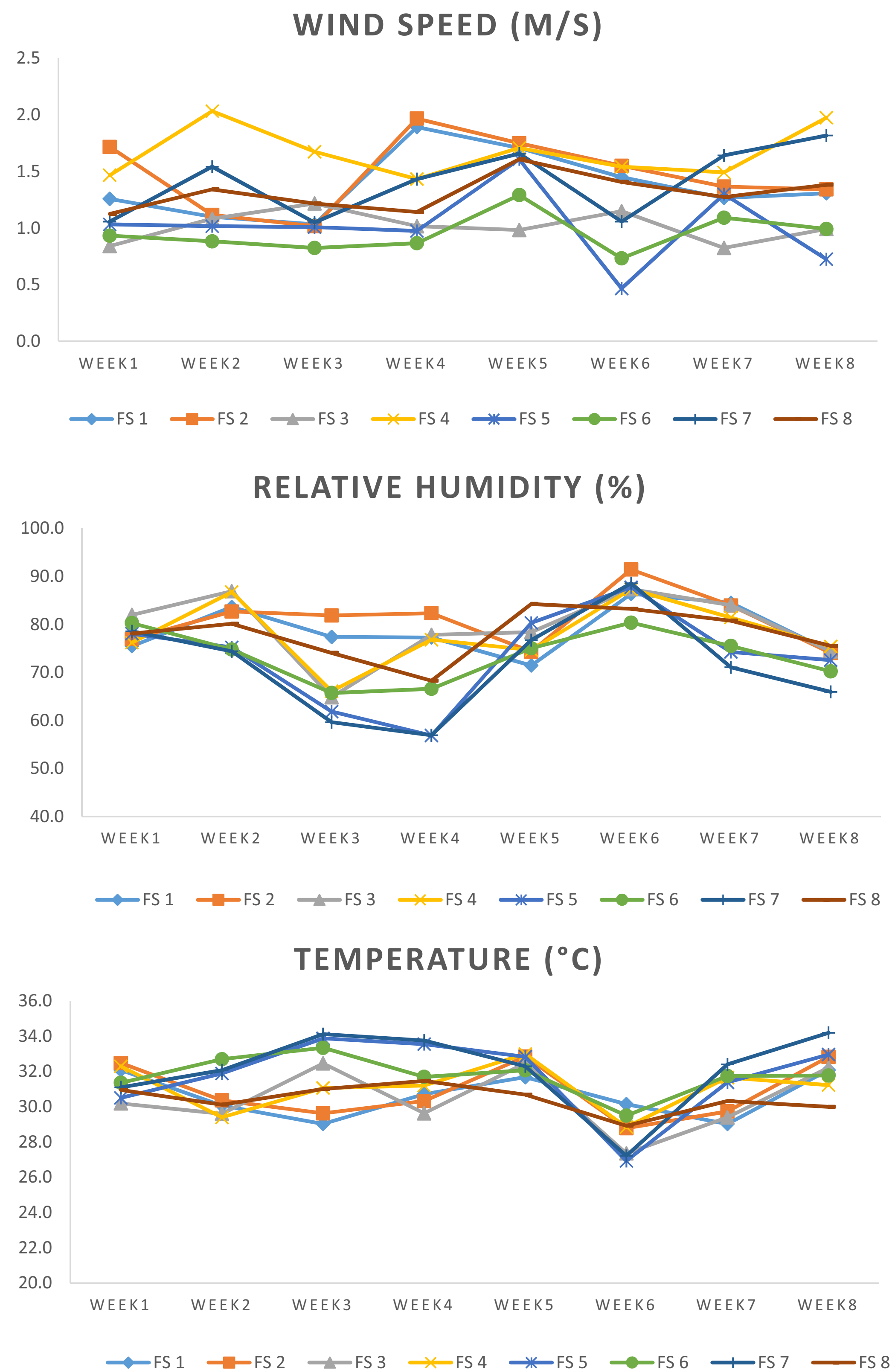


Fig. 3 Time series data of wind speed, relative humidity and temperature

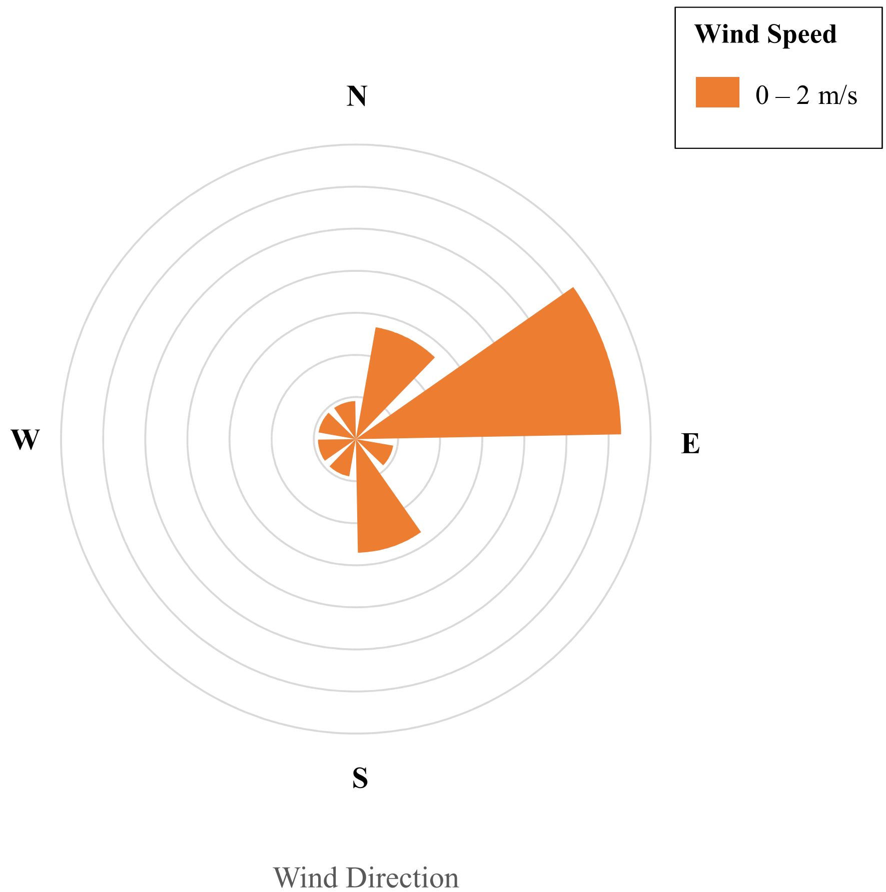


Fig. 4 Wind direction across the sampling locations

Table 1 Mean concentration of PM_{10} (μg/m^3) in March and April 2017

	March				April				Mean ± SD
	Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4	
FS 1	31.1	45.9	34.9	31.1	28.7	27.3	19.9	31.1	31.3 ± 7.4
FS 2	42.3	44.0	39.8	35.5	29.3	29.0	29.8	26.5	34.5 ± 6.8
FS 3	49.9	40.7	38.9	43.5	28.9	20.7	26.9	23.5	34.1 ± 10.5
FS 4	36.3	40.3	38.7	39.8	28.3	20.3	28.7	29.8	32.8 ± 7.1
FS 5	46.7	45.7	46.8	49.9	26.8	23.9	25.7	29.9	36.9 ± 11.3
FS 6	49.4	47.9	53.7	56.3	29.4	27.9	23.7	26.3	39.3 ± 13.7
FS 7	39.5	46.7	47.1	42.8	31.5	26.7	17.1	32.8	35.5 ± 10.5
FS 8	44.3	46.3	51.8	55.4	34.3	36.3	31.8	25.4	40.7 ± 10.4

SD Standard deviation

analysis shows that the meteorological conditions around FS 1 accounted for 17.8% of the concentration of PM_{10} in March and April 2017. In FS 2 and 3, they formed 7.6 and 12.3% of the concentrations of PM_{10}. Likewise, in FS 4 and 5 the meteorological conditions explained 16.5 and 47.5% of the concentration of PM_{10} recorded. The conditions in FS 6 and 7 accounted for 54.9 and 46.7% of the disparity in the measured concentrations of PM_{10}. The greatest influence of metrological conditions on the concentration of PM_{10} was observed at FS 8 (56.7%). The

Table 2 Relationship between meteorological parameters and the concentration of PM_{10}

	Wind Speed	Relative Humidity	Temperature
FS 1 (PM_{10})	− 0.362	− 0.033	0.056
FS 2 (PM_{10})	− 0.267	0.037	− 0.100
FS 3 (PM_{10})	− 0.243	− 0.137	0.086
FS 4 (PM_{10})	0.161	− 0.363	0.144
FS 5 (PM_{10})	− 0.031	− 0.677*	0.460
FS 6 (PM_{10})	− 0.425	− 0.430	0.455
FS 7 (PM_{10})	− 0.363	− 0.434	0.375
FS 8 (PM_{10})	− 0.704*	− 0.583*	0.598[a]

[a] Means significant at $p < 0.05$

Table 3 Influence of meteorological parameters on the concentration of PM_{10}

	Regression equation	R^2	R^2 (%)
FS 1	$Y_{PM10} = 14.71 + -11.32_{WS} + -0.06_{RH} + 1.19_{Temp}$	0.178	17.8
FS 2	$Y_{PM10} = 90.81 + -4.41_{WS} + -0.24_{RH} + -0.99_{Temp}$	0.076	7.6
FS 3	$Y_{PM10} = 152.54 + -24.05_{WS} + -0.61_{RH} + -1.50_{Temp}$	0.123	12.3
FS 4	$Y_{PM10} = 77.65 + 4.40_{WS} + -0.44_{RH} + -0.57_{Temp}$	0.165	16.5
FS 5	$Y_{PM10} = 132.13 + -1.32_{WS} + \text{-}0.92_{RH} + -0.82_{Temp}$	0.475	47.5
FS 6	$Y_{PM10} = -152.28 + -44.65_{WS} + -0.08_{RH} + 7.54_{Temp}$	0.549	54.9
FS 7	$Y_{PM10} = -94.23 + -24.19_{WS} + 0.33_{RH} + 4.36_{Temp}$	0.467	46.7
FS 8	$Y_{PM10} = -41.87 + -33.25_{WS} + 0.01_{RH} + 4.11_{Temp}$	0.567	56.7

R2 - Regression

variations observed in the concentrations of PM_{10} may not be wholesomely attributed to the prevailing meteorological conditions during the cause of sampling. Factors such as the volume of gas flared and mixing height could also be responsible for the disparity in the concentrations of PM_{10}.

Dispersion of PM_{10} from the flow stations

Figure 5 depicts the dispersion of PM_{10} from the gas flares in the flow stations in March and April, 2017. In the month of March, PM_{10} from FS 1 covered parts of Rivers, Abia, Imo, Anambra, Ebonyi and Akwa-Ibom states. In April it only extended to Rivers, Abia, Imo and Akwa-Ibom states. From FS 2, PM_{10} covered parts of Delta, Imo, Anambra and Enugu in March, while in April it spread across Bayelsa state and the Bight of Benin. Similarly, in both March and April from FS 3, PM_{10} dispersed to Delta, Imo, Abia, Anambra, Enugu and Ebonyi states. The particles emanating from FS 4 covered parts of Delta, Imo, Rivers, Anambra and Enugu states, in the month of March. While in April, it extended to Rivers, Abia, Akwa-Ibom and Imo states. At FS 5, the particles spread to Anambra, Enugu and Benue states in both months. Similarly, from FS 6, PM_{10} dispersed over Imo, Anambra, Enugu, Ebonyi and Benue states in both months. Likewise in both months, it also spread to Rivers, Imo, Enugu, Cross River, Anambra and Delta states from FS 7. Meanwhile, from FS 8 the particles spread to Imo, Anambra, Enugu, Benue and Ebonyi states, in March. While in April, it covered same states including Rivers and Cross River.

The spread of PM_{10} to these receptor areas were predicated on the prevailing climatic conditions that were obtainable as at the time sampling. It has been determined that the atmospheric boundary layer condition in study area is very stable at night and unstable during the day (Edokpa and Nwagbara 2017). By implication, ground level concentrations will be low for receptors under unstable atmospheric conditions during the day and high for receptors under stable conditions at night (Edokpa and Ede 2013).

The dispersion pattern encountered across the study area is similar to the findings of Ede and Edokpa (2017). It could also be implicated in the current soot pollution in Port Harcourt, Rivers State. Despite the low concentration of these particulate pollutants at the receptors, continuous human exposure would result in adverse health effects (Taiwo et al. 2014).

Conclusions

This study presented the concentration and dispersion of PM_{10} from eight flow stations in the Niger Delta. The link between PM_{10} and the occurrence of soot pollution in the Niger Delta makes its study a topical issue. Since these flow stations operate on a 24 hourly basis and consistently emit particulate matter, the likelihood of impacting the environment negatively is high. In FS 6 and 8, PM_{10} concentrations were higher than the recommended limit set by World Health Organisation. The dispersion of PM_{10} emitted from FS 1, 4 and 7 in April 2017, had a fitting spread over Port Harcourt City. This could be explained as one of the likely sources of soot pollution in the city. However, to adequately confirm this assertion, a further study such as receptor modeling is recommended. It can also be deduced that other parts of the country would share the burden of the risk associated with PM_{10} pollution, since its dispersion cuts across various states in Nigeria. This study suggests that the government should intervene and provide protection for the residents of these identified states through the inspection and monitoring of flare stack to ensure stricter compliance with PM_{10} limits. Furthermore, the companies operating these flow stations should be vigilant during PM_{10} monitoring and provide

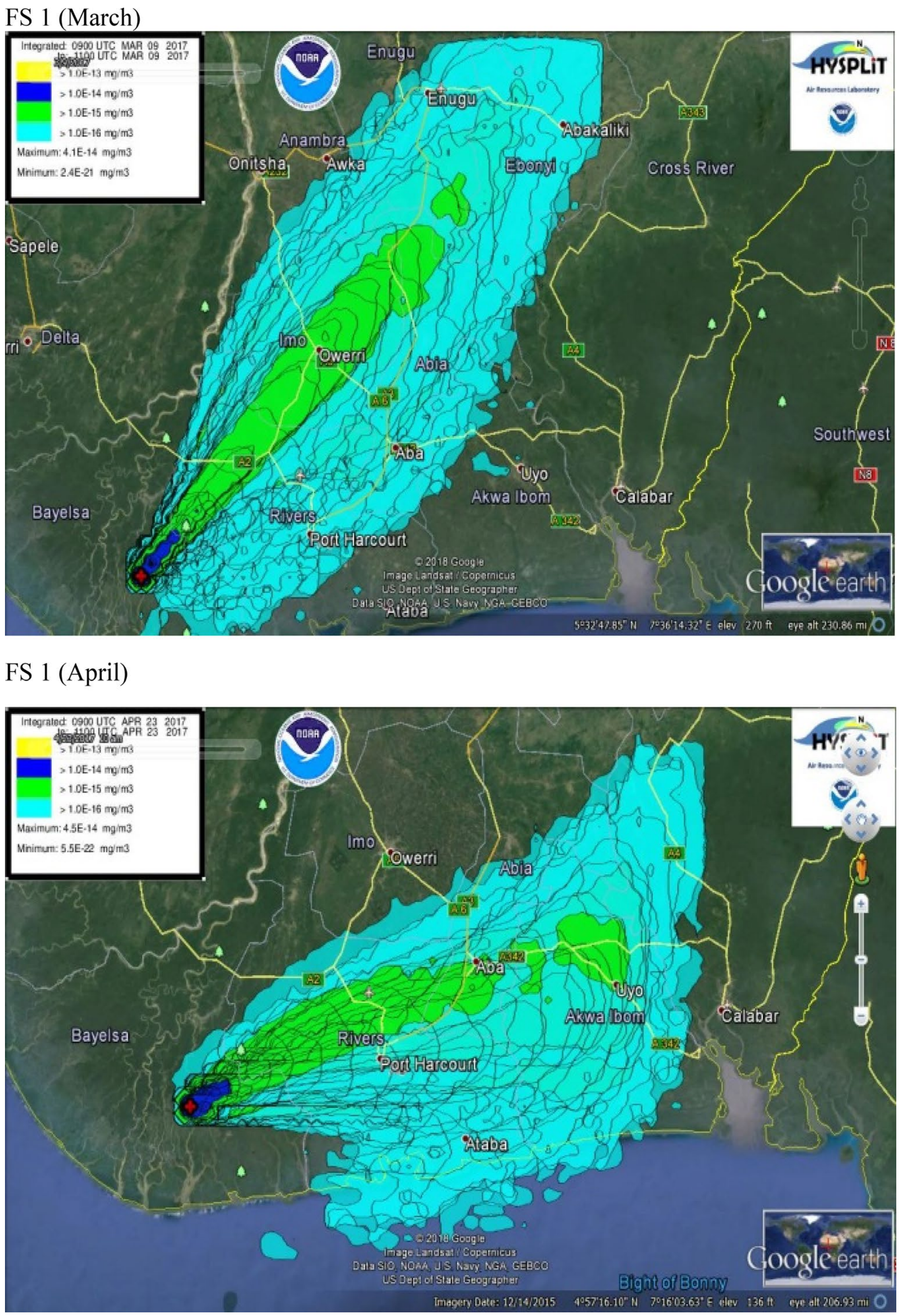


Fig. 5 Dispersion of PM_{10} from FS 1–8 in March and April 2017

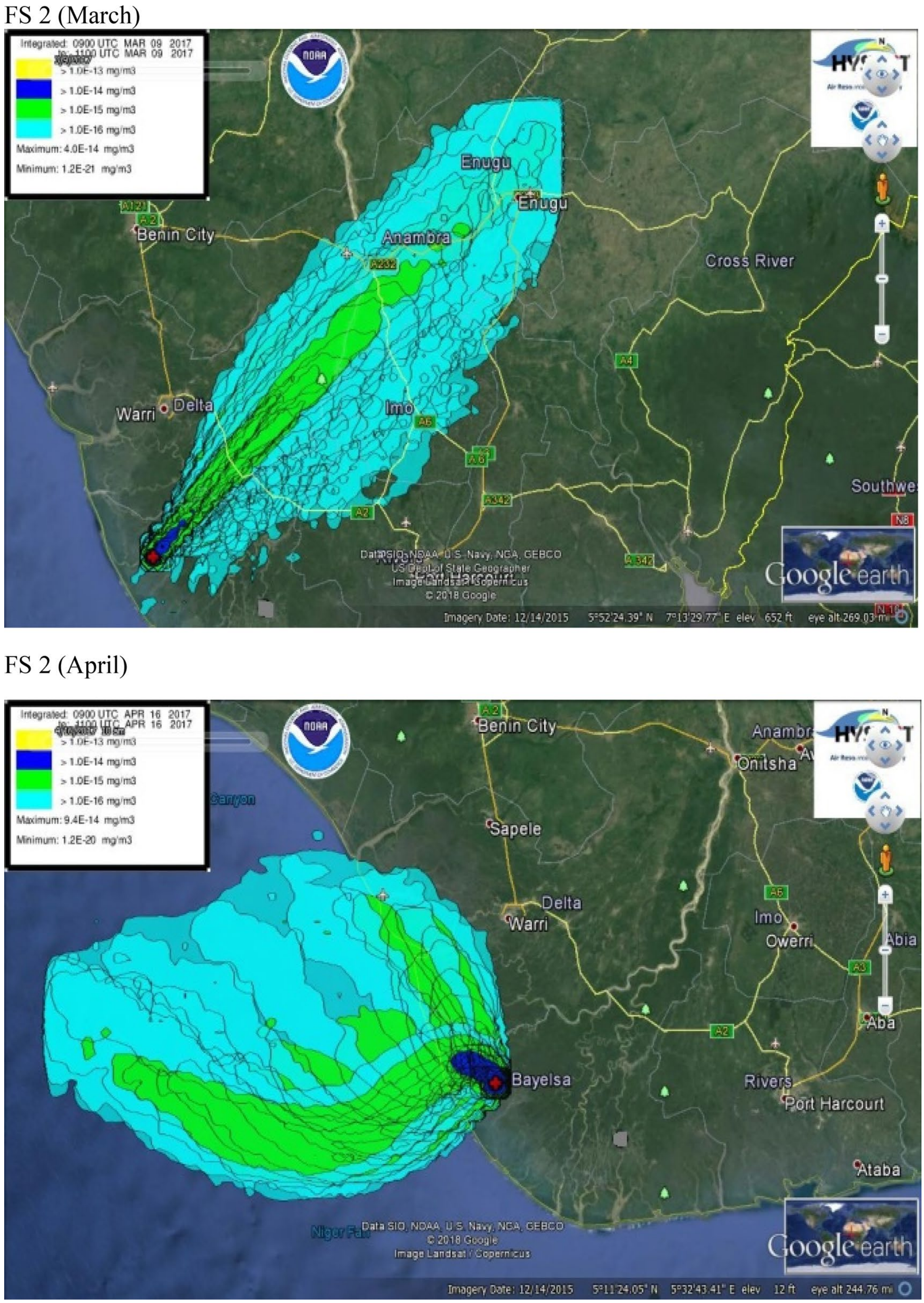
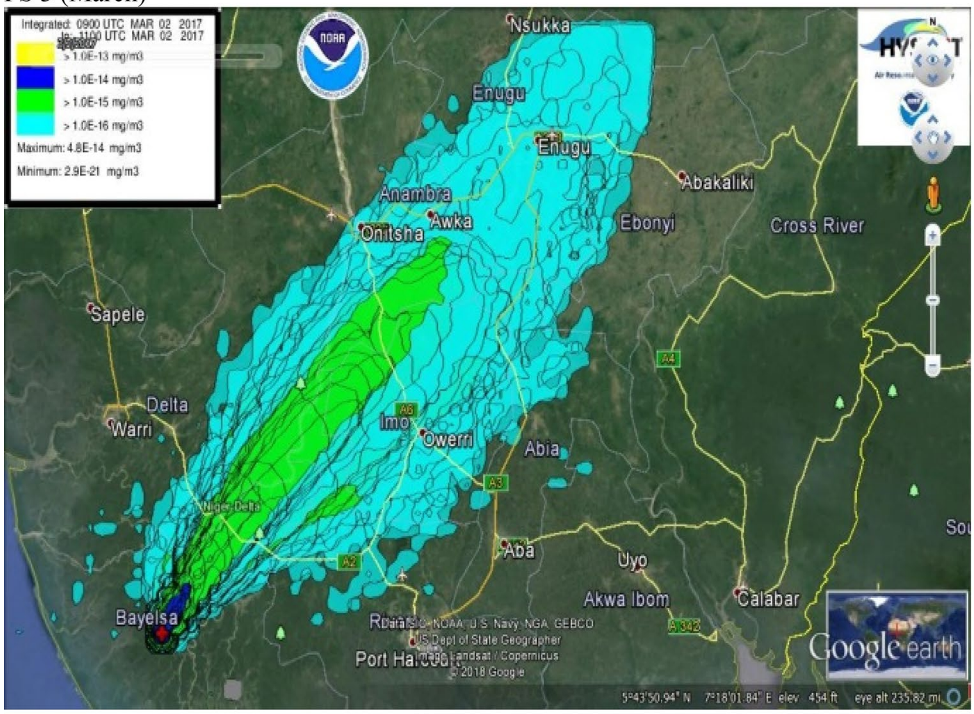


Fig. 5 continued

FS 3 (March)



FS 3 (April)

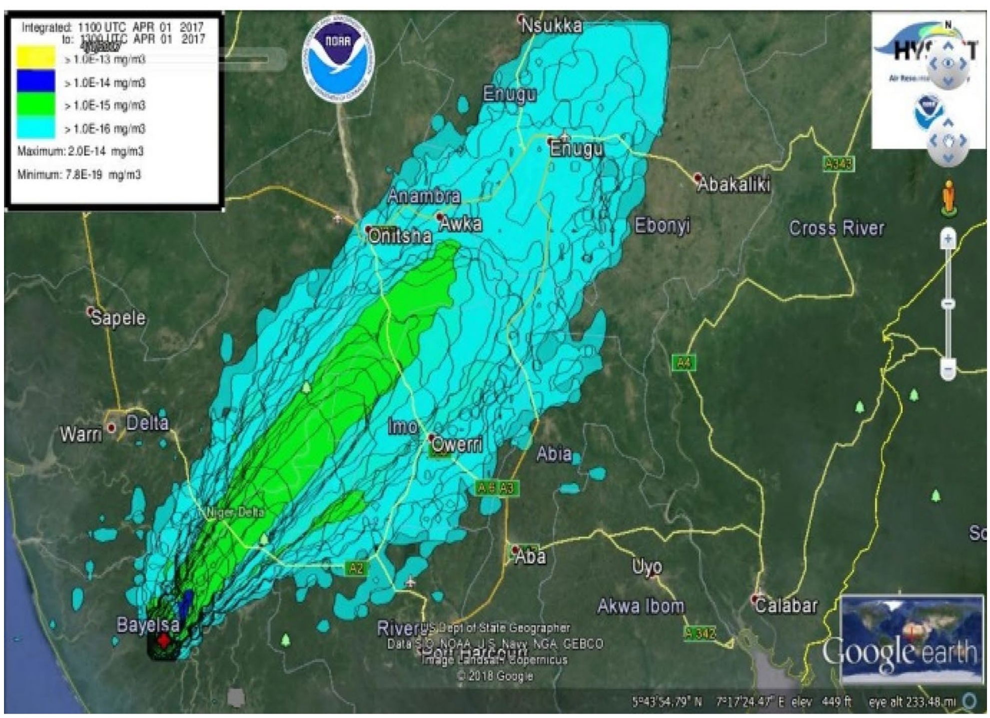
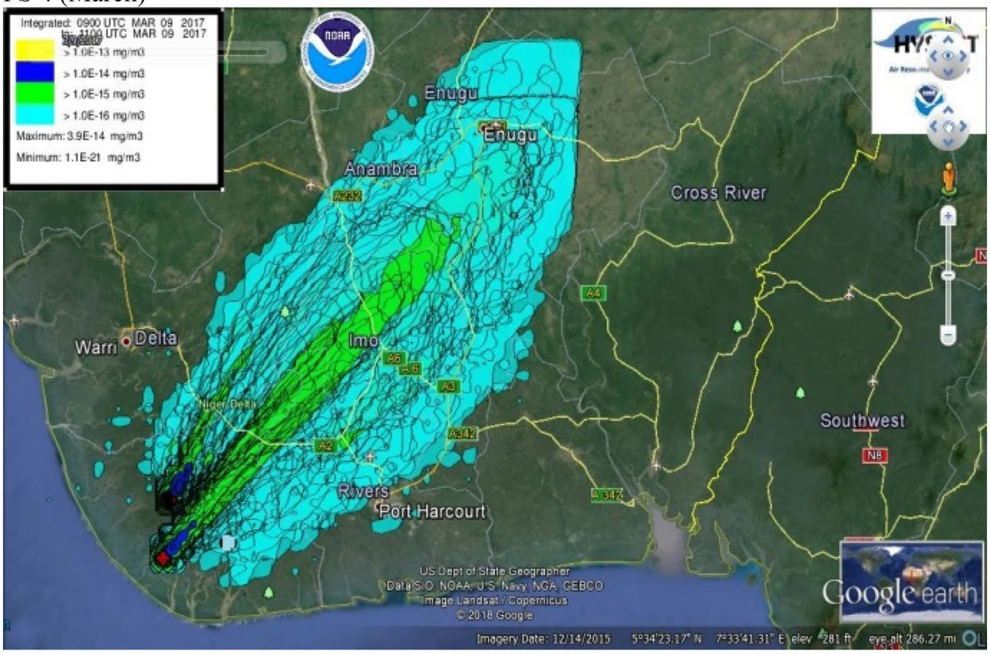
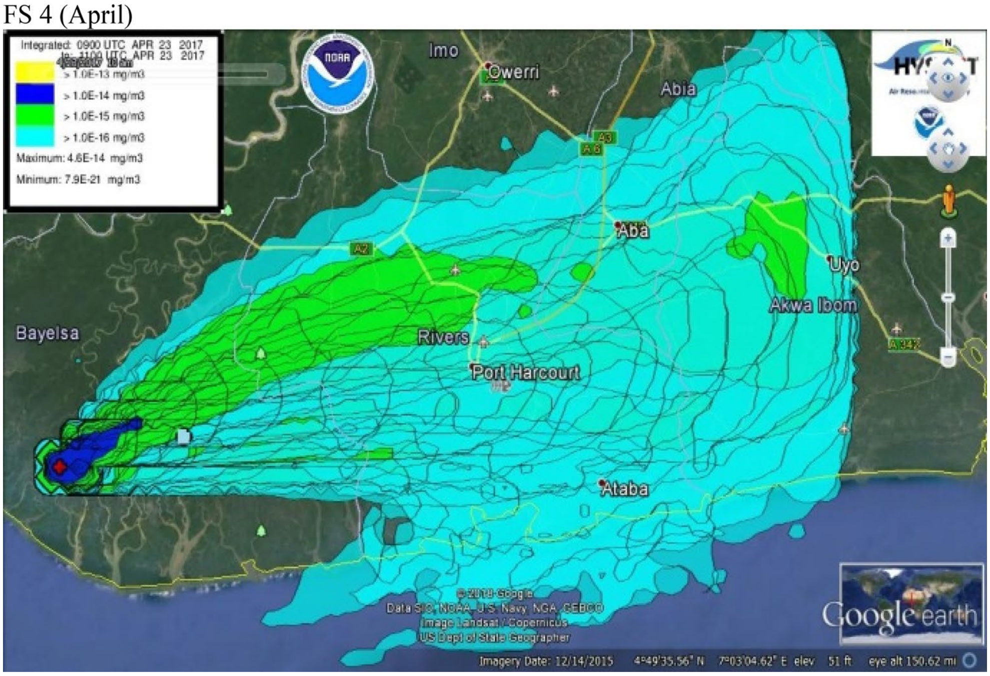


Fig. 5 continued

FS 4 (March)



FS 4 (April)



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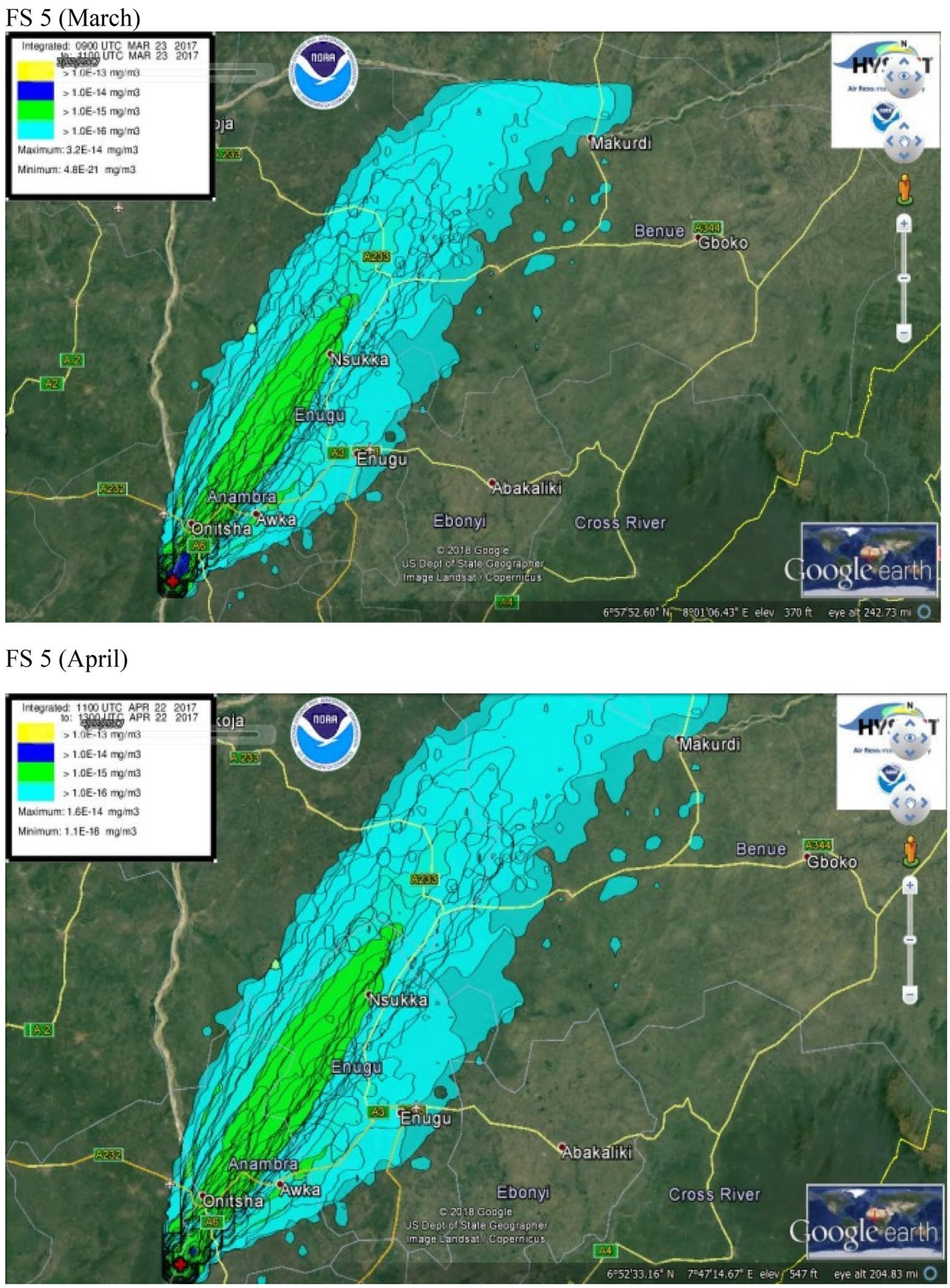
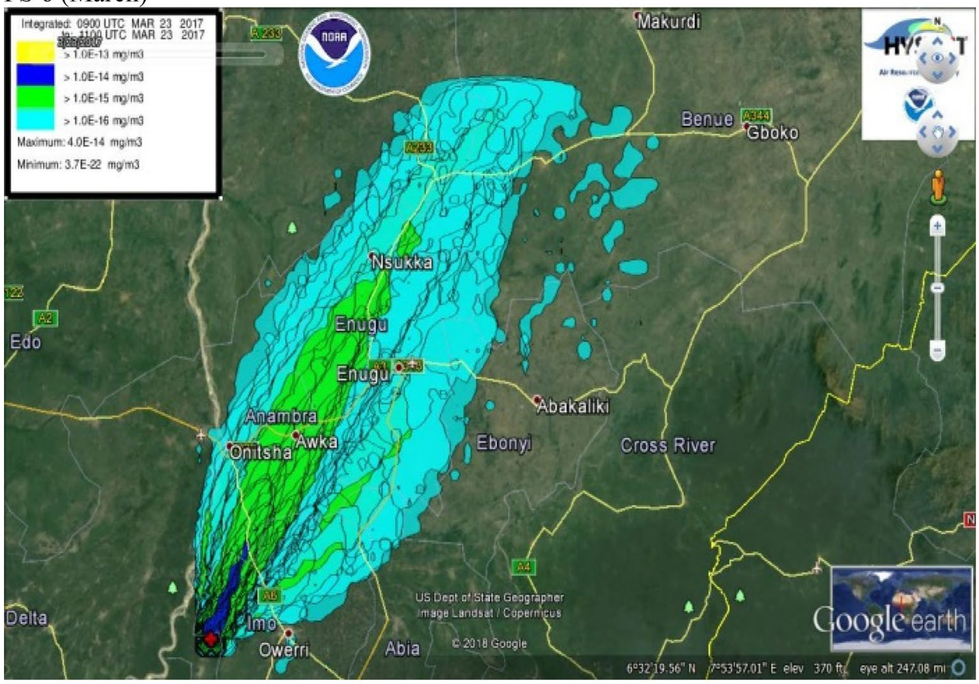
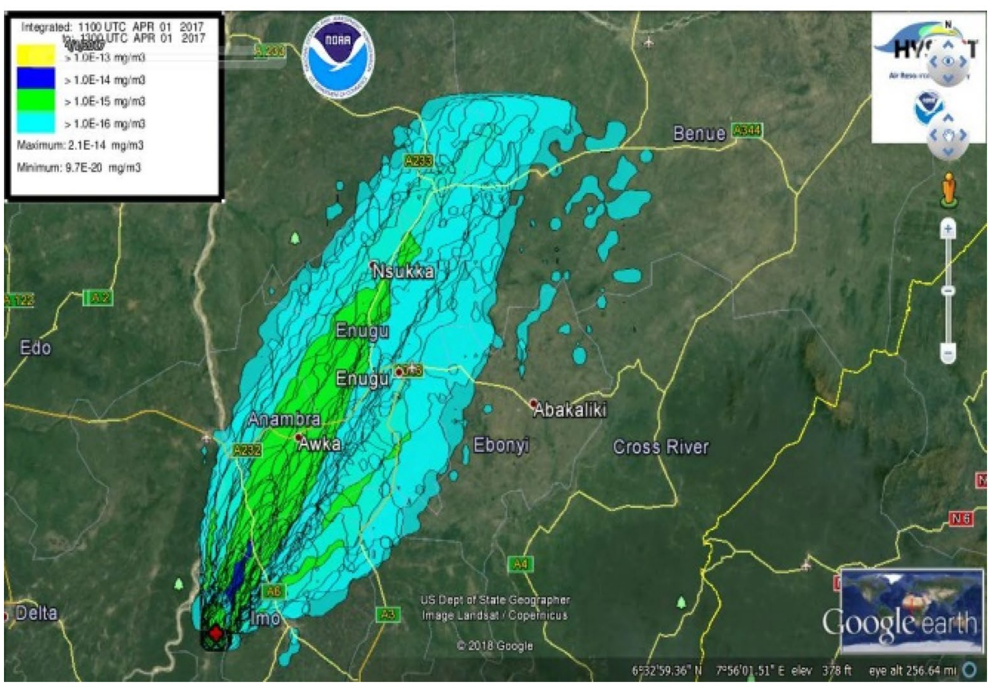


Fig. 5 continued

FS 6 (March)



FS 6 (April)



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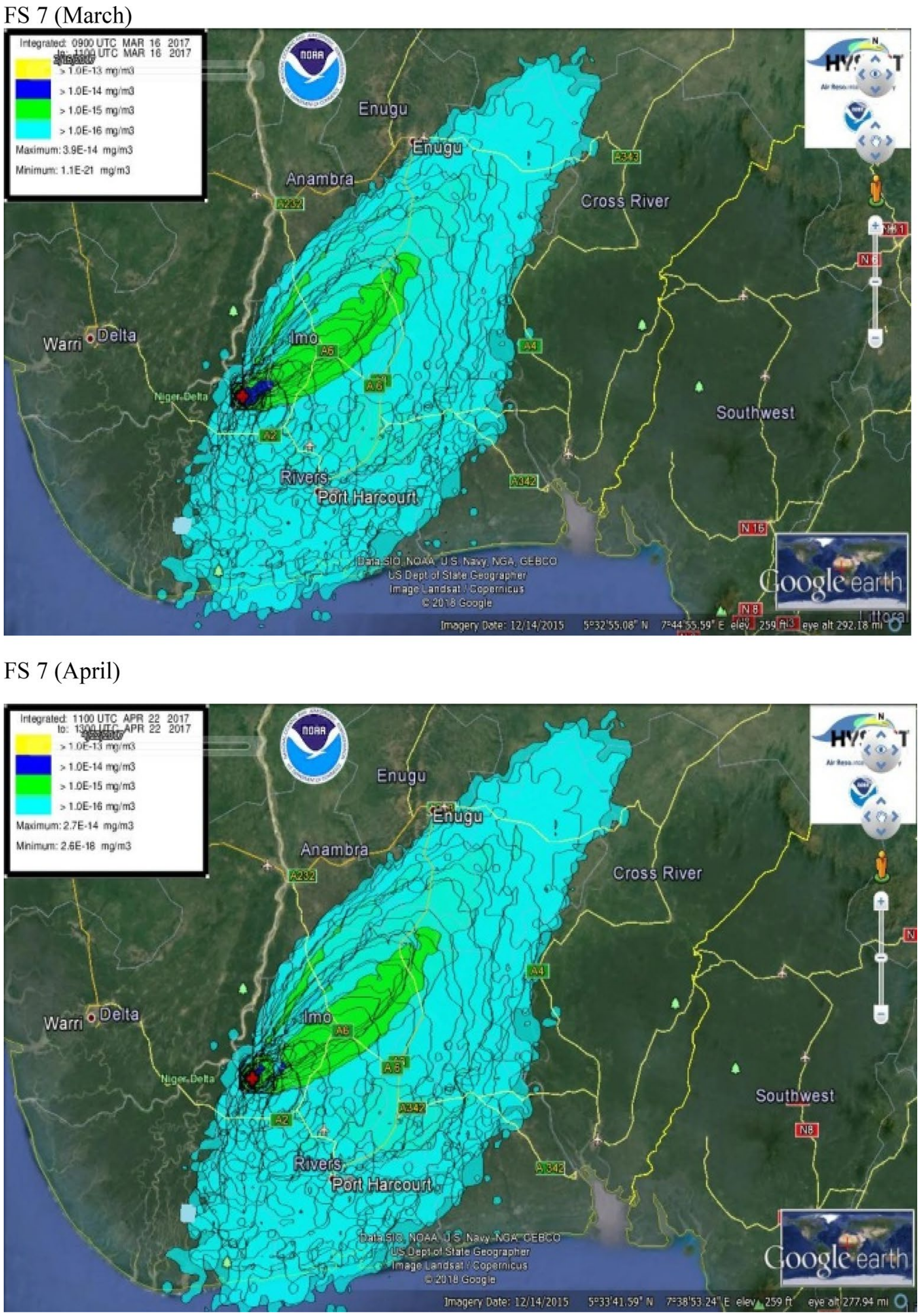
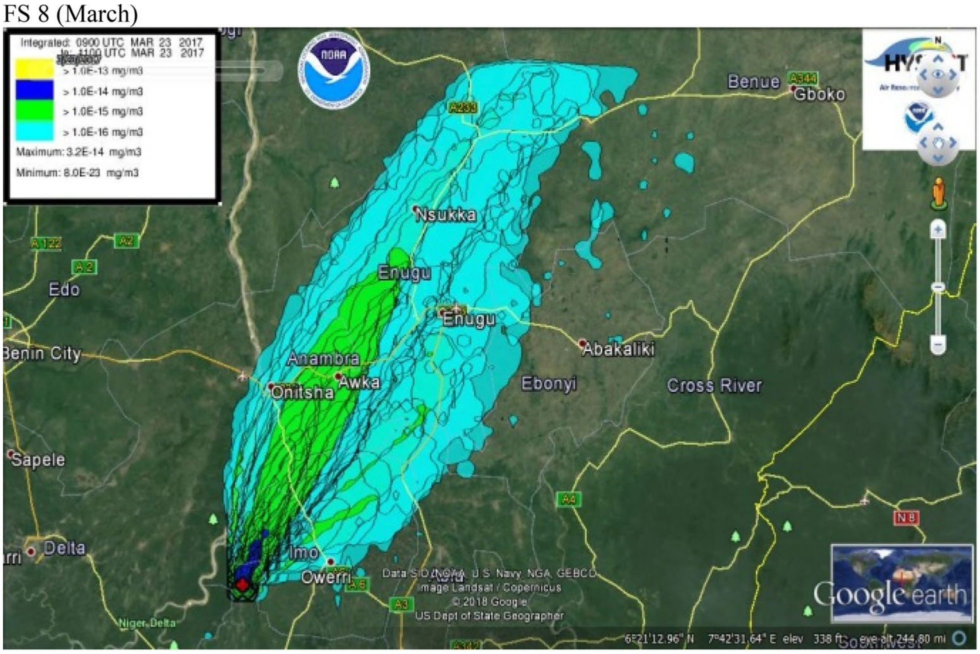


Fig. 5 continued

FS 8 (March)



FS 8 (April)

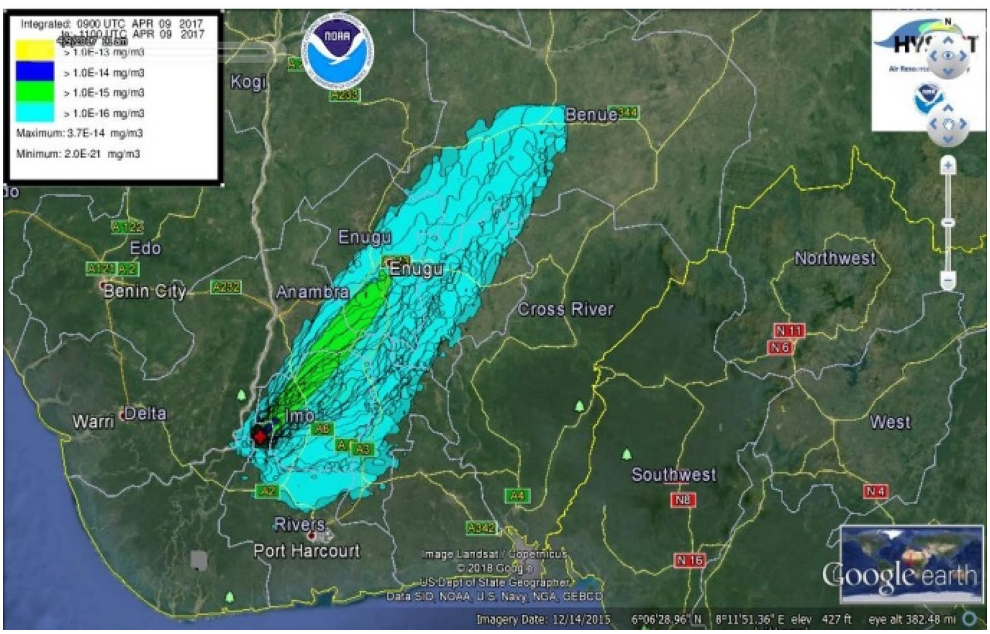


Fig. 5 continued

respiratory protection to residents, especially those within proximity to the flow stations.

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Authors' contributions
MCN Conceived and designed the research; Contributed equipment, analysis tools or data; Analysed and interpreted the data; Wrote the paper. OO and AMT: Designed the research; Contributed equipment, analysis tools or data; Supervised the research; Edited the final manuscript. All authors read and approved the final manuscript.

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Consent for publication
The authors have given their consent.

Competing interests
The authors declare that they have no competing interests.

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