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

Michael Chukwuemeka Nwosisi$^{1,*}$, Olusegun Oguntoke$^2$ and Adewale Matthew Taiwo$^2$

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 Umukor 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 andCoderre 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.
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.
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 ±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 flaring 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
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 meteorological conditions on the concentration of PM$_{10}$ was observed at FS 8 (56.7%).

**Table 1** Mean concentration of PM$_{10}$ ($\mu$g/m$^3$) in March and April 2017

| Month | Week 1 | Week 2 | Week 3 | Week 4 | Mean ± SD   |
|-------|--------|--------|--------|--------|-------------|
| March |        |        |        |        |             |
| FS 1  | 31.1   | 45.9   | 34.9   | 31.1   | 31.3 ± 7.4  |
| FS 2  | 23.1   | 44.0   | 39.8   | 35.5   | 29.3 ± 6.8  |
| FS 3  | 49.9   | 40.7   | 38.9   | 43.5   | 28.9 ± 20.7 |
| FS 4  | 46.7   | 40.3   | 38.7   | 39.8   | 28.3 ± 20.3 |
| FS 5  | 49.4   | 47.9   | 53.7   | 56.3   | 49.9 ± 23.9 |
| FS 6  | 49.4   | 47.9   | 53.7   | 56.3   | 29.4 ± 23.7 |
| FS 7  | 39.5   | 46.7   | 51.8   | 55.4   | 34.3 ± 36.3 |
| FS 8  | 44.3   | 46.7   | 47.1   | 42.8   | 31.5 ± 26.7 |
| April |        |        |        |        |             |
| FS 1  | 28.7   | 27.3   | 19.9   | 31.1   | 29.8 ± 26.5 |
| FS 2  | 29.3   | 29.0   | 29.8   | 26.5   | 34.5 ± 6.8  |
| FS 3  | 28.9   | 20.7   | 26.9   | 23.5   | 34.1 ± 10.5 |
| FS 4  | 28.3   | 20.3   | 28.7   | 29.8   | 32.8 ± 7.1  |
| FS 5  | 26.8   | 23.9   | 25.7   | 29.9   | 36.9 ± 11.3 |
| FS 6  | 29.4   | 27.9   | 23.7   | 26.3   | 39.3 ± 10.5 |
| FS 7  | 31.5   | 26.7   | 17.1   | 32.8   | 35.5 ± 10.5 |
| FS 8  | 34.3   | 36.3   | 31.8   | 25.4   | 40.7 ± 10.4 |

SD Standard deviation
Table 2 Relationship between meteorological parameters and the concentration of PM$_{10}$

| Wind Speed | Relative Humidity | Temperature |
|------------|------------------|-------------|
| FS 1 ($\text{PM}_{10}$) | $-0.362$ | $-0.033$ | $0.056$ |
| FS 2 ($\text{PM}_{10}$) | $-0.267$ | $0.037$ | $-0.100$ |
| FS 3 ($\text{PM}_{10}$) | $-0.243$ | $-0.137$ | $0.086$ |
| FS 4 ($\text{PM}_{10}$) | $0.161$ | $-0.363$ | $0.144$ |
| FS 5 ($\text{PM}_{10}$) | $-0.031$ | $-0.677^*$ | $0.460$ |
| FS 6 ($\text{PM}_{10}$) | $-0.425$ | $0.430$ | $0.455$ |
| FS 7 ($\text{PM}_{10}$) | $-0.363$ | $-0.434$ | $0.375$ |
| FS 8 ($\text{PM}_{10}$) | $-0.704^*$ | $-0.583^*$ | $0.598^*$ |

* 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 $Y_{\text{PM}_{10}} = 14.71 + -11.32W + 0.06\text{RH} + 1.19\text{temp}$ | 0.178 | 17.8 |
| FS 2 $Y_{\text{PM}_{10}} = 90.81 + 4.41W + -0.24\text{RH} + -$ | 0.076 | 7.6 |
| FS 3 $Y_{\text{PM}_{10}} = 152.54 + -24.05W + -0.01\text{RH} + -$ | 0.123 | 12.3 |
| FS 4 $Y_{\text{PM}_{10}} = 77.56 + 4.40\text{WS} + -0.44\text{RH} + -0.57\text{temp}$ | 0.165 | 16.5 |
| FS 5 $Y_{\text{PM}_{10}} = 132.13 + -13.2\text{WS} + -0.029\text{RH} + -0.82\text{temp}$ | 0.475 | 47.5 |
| FS 6 $Y_{\text{PM}_{10}} = -152.28 + -44.65\text{WS} + -$ | 0.549 | 54.9 |
| FS 7 $Y_{\text{PM}_{10}} = 94.23 + -24.19\text{WS} + 0.33\text{RH} + 4.36\text{temp}$ | 0.467 | 46.7 |
| FS 8 $Y_{\text{PM}_{10}} = -41.87 + -33.25\text{WS} + 0.01\text{RH} + 4.11\text{temp}$ | 0.567 | 56.7 |

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
Fig. 5 continued
Fig. 5 continued
Fig. 5 continued
Fig. 5 continued
Fig. 5 continued
respiratory protection to residents, especially those within proximity to the flow stations.

Acknowledgements
The authors gratefully acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model used in this publication.

Authors’ contributions
MCN conceived and designed the research; Contributed equipment, analysis tools or data; Analyzed 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.

Funding
No funding was received for this research.

Availability of data and materials
Available on request.

Code availability
Not applicable.

Ethics approval and consent to participate
Not applicable.

Consent for publication
The authors have given their consent.

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

Author details
1 Department of Environmental Management and Toxicology, Federal University of Petroleum Resources, Effurun, Delta State, Nigeria. 2 Department of Environmental Management and Toxicology, Federal University of Agriculture, Abeokuta, Ogun State, Nigeria.

Received: 21 September 2020 Accepted: 4 December 2020
Published online: 21 January 2021

References
Ana G, Sridhar M, Emerole G (2012) Polycyclic aromatic hydrocarbon burden in ambient air in selected Niger Delta communities in Nigeria. J Air Waste Manage Assoc 62(1):18–25. https://doi.org/10.1080/10473298.2011.628900
Edokpa DO, Ede PN (2017) Satellite determination of particulate load over Port Harcourt during black soot incidents. J Atmos Pollut 5(2):55–61. https://doi.org/10.1016/j.envpol.2016.05.075
Edokpa DO, Ede PN (2013) Challenges of associated gas flaring and emission propagation in Nigeria. Academia Arena 5(3):28–35
Edokpa OO, Nwagbara MO (2017) Atmospheric stability pattern over Port Harcourt. Nigeria J Atmos Pollut 3(1):7–19. https://doi.org/10.12691/jap-3-1-2
Fawole OG, Cai XM, Mackenzie AR (2016) Gas flaring and resultant air pollution: a review focusing on black carbon. Environ Pollut 216:182–197. https://doi.org/10.1016/j.envpol.2016.05.075
Gobo AE, Ideriah JK, Francis TE, Stanley HO (2012) Assessment of air quality and noise around Okrika communities, Rivers State, Nigeria. J Appl Sci Environ Manage 16(1):75–83
Hernandez G, Berry T, Shannon LW, Poyner D (2017) Temperature and humidity effects on particulate matter concentrations in a sub-tropical climate during winter. Int Proc Chem Biol Environ Eng 102:41–49
IPCC (2007) Climate change 2007: the physical science basis. contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change [Solomon, Qin S, Manning D, Chen M, Marquis Z, Averet M, Tignor KB, Miller M, H.L. (eds.)]. Cambridge University Press, Cambridge
Ismail OS, Umukoro GE (2016) Modelling combustion reactions for gas flaring and its resulting emissions. J King Saud Univ Environ Sci 28(2):130–140. https://doi.org/10.1016/j.jsues.2014.02.003
Jacobson MZ (2005) Fundamentals of atmospheric modeling, 2nd edn. Cambridge University Press, New York
Johnston MR, Codere AR (2011) An analysis of flaring and venting activity in the Alberta upstream oil and gas industry. J Air Waste Manag Assoc 61(2):190–200. https://doi.org/10.3155/1047-3289.61.2.190
Johnston M, Devillers R, Thomson K (2013) A generalized Sky-LOSA method to quantify soot/black carbon emission rates in atmospheric plumes of gas flares. Aerosol Sci Technol 47(9):1017–1029. https://doi.org/10.1080/02786826.2013.809401
Nwosisi MC, Oguntoko Q, Taiwo AM (2019) Dispersion and emission patterns of NO2 from gas flaring stations in the Niger Delta, Nigeria. Model Earth Syst Environ 6(1):73–84. https://doi.org/10.1007/s40808-019-00658-z
Oguntoko Q, Awanu AE, Annegam HJ (2012) Impact of cement factory operations on air quality and human health in Ewekoro Local Government Area, south-western Nigeria. Int J Environ Stud 69(6):934–945. DOI:https://doi.org/10.1080/00207233.2012.732751
Ramana M, Ramanathan V, Feng Y, Yoos S, Kim S, Carmichael G, Schauer J (2010) Warming influenced by the ratio of black carbon to sulphate and the black-carbon source. Nat Geosci 3:542–545. https://doi.org/10.1038/ngeo918
SPDC - Shell Petroleum Development Company (2006) Environmental Impact Assessment (EIA) of Rumuekpe (OML 22) and Etelegbe (OML 28) 3D Seismic Survey
Stein AF, Draxler RR, Rolph GD, Stunder BJ, Cohen MD, Ngan F (2015) NOAA’s HYSPLIT atmospheric transport and dispersion modeling system. Bull Am Meteorol Soc 96:2059–2077. https://doi.org/10.1175/BAMS-D-14-00110.1
Taiwo AM, Harrison RM, Shi Z (2014) A Review of receptor modelling of industrially emitted particulate matter. Atmos Environ 97:1–18. https://doi.org/10.1016/j.atmosenv.2014.07.051
Talebi A, Fatehifar E, Alizadeh R, Kahforoushan D (2014) The estimation and trial evaluation of new CO, CO2, and NOx emission factors for gas flares trially emitted particulate matter. Atmos Environ 97:109–120. https://doi.org/10.1016/j.atmosenv.2014.07.051
Torres VM, Herndon S, Allen DT (2012) Industrial flare performance at low flow conditions. 2. Steam-and air-assisted flares. Ind Eng Chem Res 51(39):12569–12576. DOI:https://doi.org/10.1021/ie202675f
USEPA (2012) Report to congress on Black Carbon. EPA-450/R-12-001, United States Environmental Protection Agency, Research Triangle Park, NC
WHO (2005) Air quality guidelines—global update 2005. https://www.who.int/airpollution/publications/aqg2005/en/

Publisher’s Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.