# **UNIVERSITY** OF BIRMINGHAM University of Birmingham Research at Birmingham

# Visibility as a proxy for air quality in East Africa

Singh, Ajit; Avis, William; Pope, Francis

DOI: 10.1088/1748-9326/ab8b12

License: Creative Commons: Attribution (CC BY)

Document Version Publisher's PDF, also known as Version of record

Citation for published version (Harvard): Singh, A, Avis, W & Pope, F 2020, 'Visibility as a proxy for air quality in East Africa', *Environmental Research* Letters, vol. 15, no. 8, 084002. https://doi.org/10.1088/1748-9326/ab8b12

Link to publication on Research at Birmingham portal

#### General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

•Users may freely distribute the URL that is used to identify this publication.

•Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research. •User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)

•Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

#### Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

### LETTER • OPEN ACCESS

# Visibility as a proxy for air quality in East Africa

To cite this article: Ajit Singh et al 2020 Environ. Res. Lett. 15 084002

View the article online for updates and enhancements.

# Environmental Research Letters

### LETTER

# Visibility as a proxy for air quality in East Africa

OPEN ACCESS

CrossMark

RECEIVED 12 February 2020

**REVISED** 9 April 2020

ACCEPTED FOR PUBLICATION 20 April 2020

published 15 July 2020

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



Ajit Singh<sup>1</sup>, William R Avis<sup>2</sup> and Francis D Pope<sup>1</sup>

<sup>1</sup> School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham B15 2TT, United Kingdom

<sup>2</sup> International Development Department, School of Government, University of Birmingham, Birmingham B15 2TT, United Kingdom E-mail: f.pope@bham.ac.uk

**Keywords:** visibility, air pollution, environmental kuznet's curve, particulate matter, East Africa, PM Supplementary material for this article is available online

### Abstract

Many urban areas in Africa do not have sufficient monitoring programs to understand their air quality. This study uses visibility as a proxy for PM pollution to provide insight into PM air pollution in three East African cities: Addis Ababa, Nairobi and Kampala, from 1974 to 2018. Overall, a significant loss in East African visibility was observed since the 1970s, where Nairobi shows the greatest loss (60%), as compared to Kampala (56%) and Addis Ababa (34%). These changes are likely due to increased anthropogenic PM emissions. Correspondingly, PM pollution levels, in Kampala, Nairobi and Addis Ababa, are estimated to have increased by 162, 182 and 62%, respectively, since the 1970s to the current period.

Distinct variations in seasonal visibility are observed, which are largely explained by changing PM sources and sinks in rainy and dry seasons. Average PM hygroscopicity is investigated by comparing average visibilities under different RH conditions. It is observed that PM hygroscopicity has decreased over time in all three cities, which is consistent with increasing emissions of PM with hygroscopicity lower than the ambient background. A large urban increment in PM is observed, with poor visibility typically occurring when the wind brings air from densely populated urban areas.

To investigate the intersection between increasing pollution, population and economic growth, changes in pollution are compared to available population growth and GDP statistics. Significant positive correlations between increasing PM and national GDP (and city population) were found for all three study cities. These cities have undergone rapid increases in population and national GDP growth (driven predominantly by study cities' economies) during the study period. This has resulted in increased rates of citywide fuel use and motorization, which provides a direct link to increased PM emissions and thus visibility loss. The study suggests that socio-economic forecasts may enable future air quality projections.

### 1. Introduction

Ambient air pollution is a major environmental issue across the world (WHO 2016, HEI 2018, Landrigan *et al* 2018). In recent years, a growing body of evidence indicates that ambient air quality in urban African locations is often poor (Petkova *et al* 2013, Desouza *et al* 2017, Pope *et al* 2018, Simwela *et al* 2018, WHO 2018, Kalisa *et al* 2019). High rates of urbanisation and population growth are affecting African air quality (Cohen *et al* 2017, Pope *et al* 2018) via processes associated with development such as large scale construction, increased energy use, vehicular emissions (Rajé *et al* 2018) and industrialization. Particulate matter (PM) air pollution is a major concern in East Africa because of the impacts upon human health (Petkova *et al* 2013, Pope *et al* 2018). Currently, there are relatively few air quality monitoring sites and networks established in East Africa; resulting in a lack of long-term air quality data to understand both air quality trends and their influences upon public health. The main obstacle to measuring and monitoring the air pollutants in these countries is the high cost of air quality monitoring equipment including their appropriate calibration and certification (Crilley *et al* 2018, 2020, Pope *et al* 2018). To this

end, there are increasing efforts to make air quality monitoring networks in the various African countries (Gaita *et al* 2014, Desouza *et al* 2017, Pope *et al* 2018, Rajé *et al* 2018) but historical data is almost non-existent. To fill this crucial data gap, visibility measurements that are recorded at major cities in East Africa can be used as a proxy for particulate matter (PM) air pollution (Singh *et al* 2017).

Visibility is a common atmospheric measurement, which can serve as a visual index for air quality (Kuo et al 2013). Visibility is the 'distance at which the contrast of a given object with respect to its background is just equal to the contrast threshold of an observer' (International Meteorological Vocabulary, World Meteorological Organization 1992, WMO 2015). Light scattering and absorption by PM and gases change the contrast between the object of interest and background. In the polluted atmosphere, visibility mainly depends upon the optical properties of PM (Bäumer et al 2008, Singh and Dey 2012). Almost all PM in the atmosphere display some degree of hygroscopicity, where particles absorb and adsorb water as a function of local relative humidity (RH) conditions. Increases in PM water content increase the size, volume, and weight of the PM (Liu et al 2012, Titos et al 2014, Singh et al 2017). Changes in the physical properties of particles, including size and composition dependent refractive index (e.g. Pope et al 2020), directly affect the ability of PM to scatter and absorb light and thus determines the visibility distance. Meteorological parameters such as temperature, wind direction, and wind speed can affect PM sources and sinks thereby influencing visibility.

Visibility data is typically available at airports, which are often located within or close to cities. This study uses historic visibility measurements as a proxy for PM in three East African cities: Addis Ababa, Kampala and Nairobi. Visibility data is typically available from at least the 1970s to present. Air quality data products from satellites are available for approximately 15–20 years (van Donkelaar *et al* 2016, 2018). Where they exist, satellite data are often poorly calibrated for the African region due to a relative lack of ground truthing (Wei *et al* 2019).

In this paper, changes in visibility are used to infer changes in PM properties. Differences in particle hygroscopicity are used to infer changes in aerosol composition. Finally, we compare the visibility derived PM data with socioeconomic factors, to investigate the potential links between them.

To date, no studies have provided a sufficiently long air quality time series to be able to assess the role of socio-economic factors upon the evolution of air pollution in East Africa. This multidisciplinary work provides the data through which to generate insight into the relationship between environmental and social-economic factors. Furthermore, this work provides a much needed baseline for East African urban air quality that can be used to assess future air quality improvement interventions in the region. The analysis techniques developed and discussed in the paper are translatable to other regions worldwide. The data gathering, analysis and data synthesis techniques developed in this paper will be of the utmost help in other regions worldwide that are similarly lacking in high quality, long term air quality monitoring.

### 2. Data

#### 2.1. Data collection

The hourly horizontal visibility data along with other meteorological parameters, such as RH, wind speed (ws) and wind direction (wd), were downloaded from National Oceanic and Atmospheric Administration (NOAA), Integrated Surface Database (ISD) system using the worldmet package in R (https://github.com/davidcarslaw/worldmet) (Lott et al 2008, Smith et al 2011, Carslaw 2017). The study sites: Kampala (Entebbe International Airport), Addis Ababa (Bole International Airport), and Nairobi (Jomo Kenyatta International Airport) are shown in figure 1. Data were downloaded for 45 years (1974 to 2018). For the same time period, the population data for study sites were obtained from the United Nations, Department of Economic and Social Affairs, Population Division (http://www.un.org/en/development/desa/population/), and national GDP data was obtained from the World Bank (https://data.worldbank.org/).

Hourly mean PM<sub>2.5</sub> (PM with diameter less than 2.5  $\mu$ m) mass concentration data were obtained from Airnow (airnow.gov) observing stations, located at the US Embassy locations in Kampala (Ggaba Road) and Addis Ababa (Entoto Street) for the (available) period of 2017–2018. Airnow observational stations at Kampala and Addis Ababa are located approximately 34 and 10 km from the meteorological sites, respectively. Airnow is run by the U.S. Environmental Protection Agency, National Oceanic and Atmospheric Administration (NOAA), National Park Service, NASA, Centers for Disease Control, and tribal, state, and local air quality agencies (White *et al* 2004, White 2010).

### 2.2. Study sites

#### 2.2.1. Nairobi (kenya)

Meteorological data were collected at Jomo Kenyatta International Airport (JKIA) (site ID 634 500– 99 999). The airport is situated in Embakasi suburb, 15 km southeast of central Nairobi (1.32°S, 36.92°E). Nairobi is the capital and largest city of Kenya, which currently accommodates more than 3.5 million inhabitants (http://worldpopulationreview.com). The major anthropogenic sources of air pollution in Nairobi are traffic, industry, and solid waste, charcoal, wood burning (Egondi *et al* 2013, Gaita *et al* 



2014). In general, there are two rainy and two dry season in Nairobi, see table 1.

### 2.2.2. Kampala (uganda)

The weather station is based at Entebbe International Airport, Kampala (site ID 637050-99999). The airport site is located on the shores of Lake Victoria in Entebbe (0.04°N, 32.44°E), which is about 40 km south-west of Kampala city centre. Entebbe itself is a significant urban centre. Kampala (0.34°N, 32.58°E) is the national and commercial capital of Uganda. This is the largest urban area in Uganda, where more than two million inhabitants live (http://worldpopulationreview.com). In general, Kampala has a tropical rainforest climate (Matagi 2002) with two wet and two dry season (table 1). The city has significant commercial and industrial activities. Over the last few years the air quality of Kampala has been significantly affected due to a growing population, industrialization, and exhaust

from unregulated cars, trucks, buses and motor bikes (Schwander *et al* 2014). Other air pollution sources like waste and charcoal burning also influence the air quality of Kampala (Ekeh *et al* 2014).

### 2.2.3. Addis ababa (ethiopia)

Meteorological data were collected at Bole International Airport (site ID 634500–99999), which is located about 5 km southeast of the Addis Ababa city centre. Addis Ababa (8.98°N, 38.76°E) is the capital and largest city of Ethiopia, which has a population of over 3.3 million (http://worldpopulationreview.com). Addis Ababa has subtropical highland climate (Araya *et al* 2010, Fazzini *et al* 2015) with four seasons in a year: summer, autumn, winter and spring (table 1). Major sources of air pollution in Addis are transport, industries and household and waste burning (Tarekegn and Gulilat 2018).

 Table 1. Approximate seasonal dates for addis ababa, kampala and nairobi.

Study location	Season 1	Season 2	Season 3	Season 4
Kampala	Dry 1 ( <i>Dec-Feb</i> )	Wet 1 ( <i>Mar-May</i> )	Dry 2 (Jun-Aug)	Wet 2 ( <i>Sept-Nov</i> )
Nairobi	Dry 1 (Hot) ( <i>Jan-mid</i>	Wet 1 (Heavy) (mid	Dry 2 (Cooler) (Jun-	Wet 2 (Light) (Oct-
Addis Ababa	Mar)	<i>Mar-May</i> )	Sep)	Nov)
	Winter (Dec-Feb)	Spring ( <i>Mar-May</i> )	Summer (Jun-Aug)	Autumn (Sep-Nov)



### 3. Methodology

### 3.1. Mathematical explanation of visibility

PM and light absorbing gases can influence the visibility via the scattering (sca) and absorption (abs) of radiation at specific wavelengths (Huang *et al* 2009). In general, visibility (V) can be represented as a function of the extinction coefficient ( $\beta_{ext}$ ) using equation (1), where visibility is inversely proportional to the  $\beta_{ext}$  (Koschmieder 1924).

$$V = K/\beta_{ext} \tag{1}$$

Here, is the Koschmieder constant, equal to 3.912, which assumes a visual contrast threshold of 2%.  $\beta_{ext}$  is the total extinction coefficient and can be explained via equation (2).

$$\beta_{ext} = \beta_{gas,sca} + \beta_{gas,abs} + \beta_{particle,sca} + \beta_{particle,abs} \quad (2)$$

Typically, the contribution of aerosol particle extinction to the visibility loss far outweighs the contribution of gases (Singh and Dey 2012, Singh *et al* 2017). Nitrogen dioxide (NO<sub>2</sub>) is the only gas with a significant visible absorption coefficient (Groblicki *et al* 1981, Singh *et al* 2017), but its contribution to the extinction coefficient/visibility is typically minor compared to the extinction caused by PM.

# 3.2. Long term temporal trends in visibility and meteorology

Trend analysis is performed upon the visibility and meteorology data set. The visibility along with other meteorological parameters at 12:00 noon for each day was averaged (mean) to determine trends over annual, decadal, seasonal and monthly cycles. The seasonal periods of all three sites are slightly different, as defined in table 1.

To understand the influence of hygroscopic growth of aerosol particle on visibility change, the data set were disaggregated into 5% RH bins. Data with RH > 97.5% is excluded because of increased likelihood of visibility disrupting fog and mist (Singh *et al* 2017).

## 4. Results and discussion

#### 4.1. Annual and seasonal visibility trends

45 years (1974–2018) of visibility data for the three study locations is investigated. Overall, the lowest mean yearly visibility  $(\pm 1 \sigma)$ , over the whole study period, was in Kampala  $(15.2 \pm 7.4 \text{ km})$  compared to Nairobi (18.6  $\pm$  6.7 km) and Addis (19.8  $\pm$  8.7 km). Figures 2 and 3 provide the annual and seasonal visibility for the three sites. Individual regressions for yearly average visibility versus year are shown in figure S1(avaliable online at stacks.iop.org/ERL/15/ 084002/mmedia). Clear downward trends in annual mean visibility is observed for all study sites (figure 2), which is understood to be due to increasing concentrations of PM. Visibility in Kampala, Nairobi and Addis Ababa decreased at a rate of 0.45, 0.52, and 0.26 km  $yr^{-1}$ , respectively, see figure S1. Nairobi has the greatest visibility loss (60%)



Figure 3. Decadal seasonal visibility over all the three study sites: (a) Kampala, (b) Nairobi and (c) Addis Ababa. The inset box provides the average visibilities over the whole study period.

over the study period compared to Kampala (56%), and Addis Ababa (34%).

Clear trends in seasonal visibility are observed for Kampala and Addis Ababa, where relatively high visibility is observed during wet/rainy periods (figures 3(a) and (c)). In particular, lower visibility with higher RH is observed during summers in Addis Ababa, while in winter higher visibility with lower RH was found. In Kampala, overall visibility was higher in both the wet seasons as compared to dry seasons.



Negligible seasonal changes in Nairobi (figures 3(a) and (b)) were observed. Overall, average visibilities for all seasons have shown a general decline for all sites from 1970s to 2010s (figures S2 and S3).

#### 4.2. Monthly and day-of-week effects on visibility

Monthly and day-of-week averaged trends of visibility and RH were determined at each study site over the whole time period. Figure 4(a) provides the monthly averaged values of visibility, where a clear and strong monthly cycle is observed for all three sites. In particular, monthly visibility trend patterns were nearly the same for Kampala and Addis Ababa, wherein visibility during the wet seasons were higher than dry months. However, due to its distinct seasons, monthly visibility trends in Nairobi were different from Kampala and Addis Ababa but the wet seasons show relatively higher visibilities compared to dry months. This suggests that wet deposition of PM is a significant factor in improving visibility and hence air quality in the region. In a previous study, Gaita et al (2014) found similar results in Nairobi, where air quality improved during wet months compared to dry months.

Day-of-the-week visibility is analysed using the whole study period. No significant day-of-week effects are observed for all three study sites. However, visibilities on Sundays are relatively higher compared to weekdays, which is likely due to lower traffic and industrial emissions on Sundays.

#### 4.3. Dependence of visibility on meteorology

RH and wind are key meteorological parameters to understand the seasonal visibility variation. Wind can influence PM concentrations by generating and depositing PM, windy conditions also lead to dilution of pollution by bringing fresh air into the city. RH influences the aerosol scattering efficiency via the hygroscopicity effect (Zhao et al 2011, Li et al 2014, Singh et al 2017). Relationships between visibility and RH and wind speed are shown in figure 5. Overall, a strong negative correlation between monthly visibility and RH was observed in Nairobi and Addis Ababa (figure 5, panels b2 and c2). However, low correlation between monthly visibility and RH was noted in Kampala, which is likely due to the small observed range of RH, which makes it difficult to observe trends above noise. Kampala's complex topographical and geographical situation may also contribute. The monitoring station in Kampala is located at the shore of the very large Lake Victoria (surface area of 68 800 km<sup>2</sup>), which influences the local meteorology of Kampala. In figure 5, panels: a3, b3 and c3 show the correlation between wind speed and visibility with good correlations for Nairobi and Addis Ababa observed, while a poor correlation was observed for Kampala, which is again likely due to smaller range of wind speed and geographical complexities of Kampala.

#### 4.3.1. Particle hygroscopicity effect upon visibility

RH influences visibility by changing particle properties (size, volume and weight). Figure 6 shows the visibility variations at different RH bins for the three study sites. Overall, a similar pattern was observed for all three sites, with visibility showing a clear dependence upon RH (figure 6(a)), indicating the bulk PM composition is hygroscopic. Figure 6(b) shows the normalized visibility trends, it indicates that the PM hygroscopicty of the bulk aerosol are similar at each site. The bulk hygroscopicity is found to be lower in





**Figure 6.** Mean visibility disaggregated by relative humidity (5% bins). Data is averaged over the whole study period (1974–2018). Panel (a) provides the absolute mean visibility, and panel (b) the normalized visibility.

East Africa when compared to sites in the UK (Singh *et al* 2017). Following the approach of Singh *et al* (2017), a hygroscopicity parameter ( $\gamma$ ) for the bulk aerosol can be derived, see discussion and figure S4 in the supplementary material for more information. In general, the aerosol hygroscopicity, as parameterized by  $\gamma$ , at the three sites decreases over time indicating that the aerosol is becoming less hygroscopic. This could indicate an increasingly greater fraction of the aerosol coming from resuspension of relatively non-hygroscopic dust from traffic emissions. Other

sources of low hygroscopicity PM could be biomass burning.

# 4.4. Influence of meteorology (wind and RH) and PM pollution upon visibility

To understand the distribution of wind speed and directions at the three study sites, wind rose plots are provided in figure 1. All three sites have distinct dominant wind directions, where the predominant wind directions in Kampala, Nairobi and Addis Ababa are



from the southwest, northeast and eastern directions, respectively.

Bivariate polar plots of visibility, relative humidity and PM<sub>2.5</sub> mass concentration were generated using the openair tool (Carslaw and Ropkins 2012) in RStudio (Allaire 2012) to explore the effect of both wind speed and wind direction upon PM concentration. In general, bivariate polar plots provide an effective graphical presentation of emission sources with wind speed and wind direction and allows for simple PM source apportionment. Figure 7 provides the graphical information on the variation of visibility and RH (and PM mass concentration) with wind speed and direction for all three study sites using two years of data (2017–2018). The length of the time period analysed here was constrained by the availability of the PM2.5 data. Bivariate polar plots of PM2.5 mass concentration were performed only for Kampala and Addis Ababa since no long-term continuous data were available for Nairobi to undertake a similar analysis.

### 4.4.1. Kampala

—Overall, high  $PM_{2.5}$  concentrations are seen with low and moderate wind speed, particularly when wind was coming from west to east direction (figure 7(a-i)). This implies a local urban emission source as this direction lies within the city area. Correspondingly, the impact of PM pollution can also be seen as visibility loss in figure 7(a-ii), where poor visibility values are observed when wind was from the same urban area. It is noted that whilst visibility reducing poor air quality comes from the direction of the major Kampala metropolitan region, the wind rose in figure 1 indicates that wind from this direction is comparatively rare. Relative humidity was also observed to be higher when wind was from this particular direction (figure 7(a-iii)). Increased visibility can be observed in high wind speed conditions, and when wind was from southeast to southwest direction (Lake Victoria area).

### 4.4.2. Addis Ababa

—Like Kampala, similar results for Addis Ababa were observed, where a strong visible influence of pollutants emissions from local and city sources can be seen in figure 7(b). In particular, high PM pollution with poor visibility coincide when air masses are from the direction (south to west) of densely populated urban area (figure 7(b-i)). Similarly, RH was high from this direction (figure 7(b-iii)). Higher visibility is observed with high wind speed and when wind was from north to east direction (green land and low population area) (figure 7(b-ii)).

### 4.4.3. Nairobi

—Overall, low visibility is typically observed at lower wind speeds and when the wind direction was from the west (densely populated urban area). Visibility values were relatively low when wind speed was lower than 4 m s<sup>-1</sup> in any direction, which indicates local source(s) of visibility degrading pollution



(figure 7(c-ii)). Relatively good visibility along with low RH values were observed when the wind originated from the northeast to southeast directions, particularly under high wind speed (>4 m s<sup>-1</sup>) conditions. A clear negative spatial correlation between RH on visibility can be seen in figure 7(c-iii), in agreement with temporal observations seen in figure 6.

Overall at the three study sites, it is found that wind speed and wind direction significantly affect the PM and hence visibility. All three sites have distinct geographical behaviour, however, poor visibility was always seen when air masses come from the direction of populated or metropolitan areas, while higher visibility was noted when air masses come from lower populated areas. It is noted, that airports themselves can become a hub for construction and urbanization, so the airports will create their own sources of PM pollution, including aircraft emissions e.g. Stacey *et al* (2020). Clear spatial impacts of RH upon visibility were observed at all sites, where greater visibility typically coincides with lower RH, and poorer visibility with higher RH conditions.

# 4.5. Index of historical air pollution in East African cities

The paucity of historic air pollution data in East African sites makes it is difficult to assess the evolution of urban air quality in the region. However, in this paper we have shown that visibility can be used as a proxy for PM pollution since visibility depends on particle scattering and absorption and is inversely related to the extinction coefficient ( $\beta_{ext}$ ) via the Koschmeider equation (1) (i.e. low visibility = high particle loading). To understand the changes in long term air quality, a decadal pollution index was calculated using visibility data for all three sites, see figure 8. The index is referenced to the visibility levels observed in the 1970s, using a simple mean over all data. Significant increases in the pollution index are observed for all three study sites. The index, suggests that PM pollution levels have increased by 162 %, 182% and 62% from the 1970s to 2010s at the Kampala, Nairobi, and Addis Ababa sites, respectively. Changes in pollution levels in these cities are likely due to a combination of increasing population, fuel use, motorization, industrialization and construction.

# 4.6. Influences of social and economic factors on visibility

Socio-economic factors contribute to the causes of PM air pollution and hence they influence visibility. The much debated Environmental Kuznets Curve (EKC) hypothesis suggests a relationship between environmental degradation and economic development (Stern et al 1996, Li et al 2007). The inverted U-shaped EKC hypothesis suggests that environmental degradation initially increases with economic growth, until an inflexion point is reached, and then further economic growth results in reduced environmental degradation, see figure S5 for a hypothetical EKC. Thus, the EKC implies economic development can be a significant and powerful factor for the environment throughout a region's development. Previous studies mention that EKC hypothesis can be explained factors such as adoption/diffusion of clean technologies, globalisation, foreign trade and investment (Copeland and Taylor 1995, Reppelin-Hill 1999, Dasgupta et al 2002). The inverted U-shape predicted by the EKC can be approximated by a lognormal curve (Gangadharan and Valenzuela 2001, Kahuthu 2006, Halkos 2011).

To investigate the influences of socio-economic factors upon visibility, the relationship between study city population, countrywide GDP and visibility for the study sites are analysed (figures 9 and S6).



Major increases in population growth and national GDP are observed over the last five decades in all three study cities. GDP data for the individual cities were not available, but it is noted that the country GDP is predominantly driven by capital cities in the countries of interest. A clear decline in visibility is found to coincide with population growth over the last five decades (figure 9(a)), with a significant anti-correlation between city population and visibility in all three cities observed: Kampala  $(R^2 = 0.81)$ , Nairobi  $(R^2 = 0.91)$ , and Addis Ababa  $(R^2 = 0.98)$ . The growth in population and GDP results in increased rates of fuel use and motorization (Sachs et al 2004, Floater et al 2014), which provides a direct and causal link to increased PM emissions and thus visibility loss. In future studies, if the data becomes available, it would be good to investigate the role of population density in addition to total population on air pollution. In figure 9(b) (and S6b),  $\beta_{ext}$  is compared to GDP using decadal means. For all three

study cities, an increasing trend of  $\beta_{ext}$  with GDP is observed in which the relationship over the available data range is well modelled using a natural log function. Overall, the results suggest that the observed shape of the curves are consistent with EKC hypothesis with East African urban areas entering a phase of a weakening positive relationship between outdoor air quality and GDP. However, these results do not definitively prove the EKC hypothesis for the region and pollutant studied.

### **5.** Conclusions

The long-term trends in visibility for three East African sites have been analysed, where study locations are within or close to the capital cities of Uganda (Kampala), Kenya (Nairobi) and Ethiopia (Addis Ababa). Overall, the lowest long-term average (from 45 years of data) visibility was found in Kampala  $(15.2 \pm 7.4 \text{ km})$  followed by Nairobi  $(18.6 \pm 6.7 \text{ km})$ 

and Addis Ababa (19.8  $\pm$  8.7 km), which is likely due to higher PM pollution in Kampala as compared to the two other cities. In the last five decades, a significant reduction in visibility at the study sites has been observed, where Nairobi has shown highest visibility loss (60%) as compared to Kampala (56%), and Addis Ababa (34%). Correspondingly, the rate of change of visibility particularly in Nairobi (0.52 km  $yr^{-1}$ ) was higher compared to Kampala  $(0.45 \text{ km yr}^{-1})$  and Addis Ababa (0.26 km yr<sup>-1</sup>). Visibility was found to be lowest during the dry months and highest in wet months. Strong correlations between monthly RH and visibility were found for Nairobi and Addis Ababa. Kampala with a more constant RH throughout the seasons did not show a similar correlation. At all study sites, visibility is found to be higher on Sundays as compared to the other days of week, which is most likely due to reduced traffic and industrial emissions on Sundays. PM hygroscopicity could be inferred from the RH dependence on the visibility data, with a similar hygroscopicity observed for all study sites. Moreover, aerosol hygroscopicity at the three sites decreases over time indicating that the aerosol is becoming less hygroscopic in East African urban areas.

Using visibility as a proxy for PM air pollution, it is observed that the three studied East African cities have undergone significant changes in pollution levels over the past five decades. The conversion of visibility to extinction coefficient, suggests that the PM levels of Kampala, Nairobi and Addis Ababa have increased by 162%, 182% and 62%, respectively, since the 1970s.

To identify locations and sources of visibility influencing PM, the relationship between visibility and wind (speed and direction) was analysed using bivariate polar plots. Overall, poor visibility was found when air masses passed over urban area, while improved visibility was observed when air masses originated from low populated areas. In addition, the bivariate polar plots provided further evidence of anti-correlation between visibility and PM pollution (and RH) for all three sites.

Air pollution is a pressing and multi-sectoral development challenge, representing a major health, economic and social threat to cities globally. It is inextricably linked to how we plan, manage and live in these cities. To understand the effect of changes in social and economic factors, the relationship between visibility (a proxy for PM and hence air quality) and country GDP and study city population was investigated. A significant anti-correlation between city population and visibility was found in all three study cities. PM pollution was measured by the changes in the extinction coefficient ( $\beta_{ext}$ ). The populations of study cities have increased rapidly over the study period. In addition to the massive population growth, the GDP per capita in these cities also grew significantly resulting in much increased rates of fuel use and motorization, which provides a direct and causal link to increased PM emissions and thus visibility reduction in these cities.

The three study cities are rapidly developing and over at least the short-term will likely experience further increases in PM pollution due to increasing urbanization and economic development. Poor air quality acts as a brake on development through increasing market costs, including: higher expenditure on health, loss of labour productivity, and the impact of illness on education. To reduce the impacts of future air pollution upon these cities, a systematic approach should be applied to understand the causes and effects of air pollution, through which air quality degradation can be decoupled from future economic development.

### Acknowledgments

The work is funded by the UK Department for International Development (DFID) via the East Africa Research Fund (EARF) grant 'A Systems Approach to Air Pollution (ASAP) East Africa' and EPSRC (Global Challenges Research Fund IS2017).

### Data availability

The data that support the findings of this study are openly available at the following URL/DOI/source.

1. Visibility and other meteorological data can be downloaded from National Oceanic and Atmospheric Administration (NOAA), Integrated Surface Database (ISD) system using the worldmet package in R (https://github.com/davidcarslaw/worldmet)

2. Population: www.un.org/en/development/desa/ population

3. GDP: https://data.worldbank.org/

### **ORCID** iDs

Ajit Singh (a) https://orcid.org/0000-0003-0986-2064 William R Avis (a) https://orcid.org/0000-0002-7207-3992

Francis D Pope () https://orcid.org/0000-0001-6583-8347

### References

- Allaire J 2012 RStudio: integrated development environment for R (Boston, MA) pp 770
- Araya A, Keesstra S and Stroosnijder L 2010 A new agro-climatic classification for crop suitability zoning in northern semi-arid Ethiopia Agric. For. Meteorol. 150 1057–64
- Bäumer D, Vogel B, Versick S, Rinke R, Möhler O and Schnaiter M 2008 Relationship of visibility, aerosol optical thickness and aerosol size distribution in an ageing air mass over South-West Germany Atmos. Environ. 42 989–98
- Carslaw D 2017 worldmet: import surface meteorological data from NOAA integrated surface database (ISD) GitHub repository (available at: http://github.com/ davidcarslaw/worldmet)

<sup>4.</sup> PM2.5 mass concentrations: www.airnow.gov

- Carslaw D C and Ropkins K 2012 Openair—an R package for air quality data analysis *Environ. Model. Softw.* **27** 52–61
- Cohen A J, Brauer M, Burnett R, Anderson H R, Frostad J, Estep K, Balakrishnan K, Brunekreef B, Dandona L and Dandona R 2017 Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the global burden of diseases study 2015 Lancet 389 1907–18
- Copeland B R and Taylor M S 1995 Trade and the environment: a partial synthesis *Am. J. Agric. Econ.* **77** 765–71
- Crilley L R, Shaw M, Pound R, Kramer L J, Price R, Young S, Lewis A C and Pope F D 2018 Evaluation of a low-cost optical particle counter (Alphasense OPC-N2) for ambient air monitoring *Atmos. Meas. Tech.* 709–20
- Crilley L R *et al* 2020 Effect of aerosol composition on the performance of low-cost optical particle counter correction factors *Atmos. Meas. Tech.* **13** 1181–93
- Dasgupta S, Laplante B, Wang H and Wheeler D 2002 Confronting the environmental Kuznets curve J. Econ. Perspect. 16 147–68
- Desouza P, Nthusi V, Klopp J M, Shaw B E, Ho W O, Saffell J, Jones R and Ratti C 2017 A Nairobi experiment in using low cost air quality monitors *Clean Air J. Tydskrif Vir Skoon Lug.* 27 12–42
- Egondi T, Kyobutungi C, Ng N, Muindi K, Oti S, Vijver S V D, Ettarh R and Rocklöv J 2013 Community perceptions of air pollution and related health risks in Nairobi slums *Int. J. Environ. Res. Public Health* **10** 4851–68
- Ekeh O, Fangmeier A and Müller J 2014 Quantifying greenhouse gases from the production, transportation and utilization of charcoal in developing countries: a case study of Kampala, Uganda *Int. J. Life Cycle Assess.* **19** 1643–52
- Fazzini M, Bisci C and Billi P 2015 *The climate of Ethiopia, Landscapes and Landforms of Ethiopia* (Dordrecht: Springer) pp 65–87
- Floater G, Rode P, Robert A, Kennedy C, Hoornweg D, Slavcheva R and Godfrey N 2014 Cities and the New Climate Economy: the transformative role of global urban growth
- Gaita S M, Boman J, Gatari M J, Pettersson J B and Janhäll S 2014 Source apportionment and seasonal variation of PM 2.5 in a sub-saharan african city: Nairobi, Kenya Atmos. Chem. Phys. 14 9977–91
- Gangadharan L and Valenzuela M R 2001 Interrelationships between income, health and the environment: extending the environmental Kuznets curve hypothesis *Ecol. Econ.* **36** 513–31
- Groblicki P J, Wolff G T and Countess R J 1981 Visibility-reducing species in the Denver "brown cloud"—I. Relationships between extinction and chemical composition *Atmos. Environ.* 15 2473–84
- Halkos G 2011 Environment and economic development: determinants of an EKC hypothesis
- HEI 2018 State of global air 2018, special report, Boston, MA: Health Effects Institute
- Huang W, Tan J, Kan H, Zhao N, Song W, Song G, Chen G, Jiang L, Jiang C and Chen R 2009 Visibility, air quality and daily mortality in Shanghai, China *Sci. Total Environ.* 407 3295–300
- WMO 1992 International Meteorological Vocabulary, World Meteorological Organization (Geneva)
- Kahuthu A 2006 Economic growth and environmental degradation in a global context *Environ. Dev. Sustainability* **8** 55–68
- Kalisa E, Archer S, Nagato E, Bizuru E, Lee K, Tang N, Pointing S, Hayakawa K and Lacap-Bugler D 2019 Chemical and biological components of urban Aerosols in Africa: current status and knowledge gaps *Int. J. Environ. Res. Public Health* 16 941
- Koschmieder H 1924 Theorie der horizontalen Sichtweite Beitr. Phys. Freien. Atmos. 12 33–55
- Kuo C-Y, Cheng F-C, Chang S-Y, Lin C-Y, Chou C C, Chou C-H and Lin Y-R 2013 Analysis of the major factors affecting the visibility degradation in two stations J. Air Waste Manage. Assoc. 63 433–41

- Landrigan P J, Fuller R, Acosta N J, Adeyi O, Arnold R, Baldé A B, Bertollini R, Bose-O'Reilly S, Boufford J I and Breysse P N J T L 2018 The Lancet commission on pollution and health *Lancet* **391** 462–512
- Li H, Grijalva T and Berrens R P 2007 Economic growth and environmental quality: a meta-analysis of environmental Kuznets curve studies *Econ. Bull.* **17** 1–11
- Li Y, Lau A, Wong A and Fung J J J O G R A 2014 Decomposition of the wind and nonwind effects on observed year-to-year air quality variation *Atmospheres* **119** 6207–20
- Liu X, Zhang Y, Cheng Y, Hu M and Han T 2012 Aerosol hygroscopicity and its impact on atmospheric visibility and radiative forcing in Guangzhou during the 2006 PRIDE-PRD campaign Atmos. Environ. 60 59–67
- Lott N, Vose R, Del Greco S, Ross T, Worley S and Comeaux J 2008 The integrated surface database: partnerships and progress, extended abstracts 24th Conf. on Interactive Information and Processing Systems
- Matagi S V 2002 Some issues of environmental concern in Kampala, the capital city of Uganda *Environ. Monit. Assess* 77 121–38
- Petkova E P, Jack D W, Volavka-Close N H and Kinney P L 2013 Particulate matter pollution in african cities. air quality *Atmos. Health* 6 603–14
- Pope F D, Gatari M, Ng'ang'a D, Poynter A and Blake R 2018 Airborne particulate matter monitoring in Kenya using calibrated low-cost sensors *Atmos. Chem. Phys.* **18** 15403–18
- Pope F D, Dennis-Smither B J, Griffiths P T, Clegg S L and Cox R A 2010 Studies of single aerosol particles containing malonic acid, glutaric acid, and their mixtures with sodium chloride.
  I. Hygroscopic growth J. Phys. Chem. A 114 5335–41
- Rajé F, Tight M and Pope F D 2018 Traffic pollution: a search for solutions for a city like Nairobi *Cities* **82** 100–7
- Reppelin-Hill V 1999 Trade and environment: an empirical analysis of the technology effect in the steel industry *J. Environ. Econ. Manage.* **38** 283–301
- Sachs J, Mcarthur J W, Schmidt-Traub G, Kruk M, Bahadur C, Faye M and Mccord G 2004 Ending Africa's poverty trap *Brookings Pap. Econ. Act.* **2004** 117–240
- Schwander S, Okello C D, Freers J, Chow J C, Watson J G, Corry M and Meng Q 2014 Ambient particulate matter air pollution in mpererwe district, Kampala, Uganda: a pilot study J. Environ. Public Health 2014
- Simwela A, Xu B, Mekondjo S S and Morie S 2018 Air quality concerns in Africa: a literature review *Int. J. Sci. Res. Publ.* **8** 588–94
- Singh A, Bloss W J and Pope F D 2017 60 years of UK visibility measurements: impact of meteorology and atmospheric pollutants on visibility Atmos. Chem. Phys. 17 2085–101
- Singh A and Dey S 2012 Influence of aerosol composition on visibility in megacity Delhi *Atmos. Environ.* **62** 367–73
- Smith A, Lott N and Vose R 2011 The integrated surface database: recent developments and partnerships Bull. Am. Meteorol. Soc. 92 704–8
- Stacey B, Harrison R M and Pope F 2020 Evaluation of ultrafine particle concentrations and size distributions at London Heathrow Airport *Atmos. Environ.* **222** 117148
- Stern D I, Common M S and Barbier E B 1996 Economic growth and environmental degradation: the environmental Kuznets curve and sustainable development *World Dev.* **24** 1151–60
- Tarekegn M and Gulilat T 2018 Trends of ambient air pollution and the corresponding respiratory diseases in Addis Ababa *Res. Rep. Toxi* 2 5
- Titos G, Jefferson A, Sheridan P, Andrews E, Lyamani H, Alados-Arboledas L and Ogren J 2014 Aerosol light-scattering enhancement due to water uptake during the TCAP campaign *Atmos. Chem. Phys.* **14** 7031–43
- van Donkelaar A, Martin R V, Brauer M, Hsu N C, Kahn R A, Levy R C, Lyapustin A, Sayer A M and Winker D M 2016 Global estimates of fine particulate matter using a combined geophysical-statistical method with information from satellites *Environ. Sci. Technol.* **50** 3762
- van Donkelaar A, Martin R V, Brauer M, Hsu N C, Kahn R A, Levy R C, Lyapustin A, Sayer A M and Winker D M 2018.

Global annual PM2.5 grids from MODIS, MISR and seawifs aerosol optical depth (AOD) with GWR 1998–2016 (Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC))

- Wei J, Peng Y, Mahmood R, Sun L and Guo J 2019 Intercomparison in spatial distributions and temporal trends derived from multi-source satellite aerosol products *Atmos. Chem. Phys.* **19** 7183–207
- White J E 2010 AIRNow-International: the future of the United States real-time air quality reporting and forecasting program with GEOSS participation accessed 5.
- White J E, Wayland R A, Dye T S and Chan A C 2004 AIRNow air quality notification and forecasting system (*Beijing, China*:

*Beijing International Environment Forum September*) pp 14–15

- WHO 2016 WHO's Urban Ambient Air Pollution Database–Update 2016 (Geneva: World Health Organization)
- WHO 2018 Ambient (outdoor) air quality and health (Geneva: World Health Organization)
- WMO 2015 Manual on the Global Observing System, Volume I Global Aspects, World Meteorological Organization WMO-No. 544 (Geneva)
- Zhao P, Zhang X, Xu X and Zhao X 2011 Long-term visibility trends and characteristics in the region of Beijing, Tianjin, and Hebei, China *Atmos. Res.* **101** 711–18