Strengths and weaknesses of the WHO urban air pollutant database

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**ABSTRACT**

The 2018 World Health Organization (WHO) global ambient air quality database is an impressive piece of data compilation. It has particulate matter (PM\textsubscript{10}) monitoring data for 3,570 cities in 97 countries, and PM\textsubscript{2.5} data for 2,628 cities in 81 countries. The database uses PM\textsubscript{10} and PM\textsubscript{2.5} data from established public air quality monitoring systems, which includes pollutants such as sulphates, nitrates and black carbon. These pollutants can penetrate deep into the lungs and the cardiovascular system posing the greatest risk to human health. Unsurprisingly, the WHO database reports relatively low levels of urban PM pollution in high-income countries in Western Europe, the Americas, the Western Pacific, and Oceania and high levels in low-and middle-income (LMI) countries in Africa, Latin America, and Southeast Asia, and even in high-income countries in Latin America. Lack of funding and inadequate staffing in LMI countries are key barriers to effective air pollution reduction. The WHO database has led people and the media to compare cities and draw inaccurate and misleading conclusions, which occurred with the WHO’s 2016 global urban ambient air quality database. In this paper, we investigate the strengths and weaknesses of the 2018 database with respect to several criteria (e.g. selection of pollutants, completeness, spatial and temporal representativeness, and quality assurance and quality control) and make recommendations for improvements.

**Keywords:** air pollutants, completeness, comparability, representativeness, data coverage
Introduction

The 2018 update of the World Health Organization (WHO) global ambient air quality database for coarse and fine particulate matter (PM$_{10}$ and PM$_{2.5}$) concentrations resulted in the media, and international organisations awarding the ‘Most Polluted City’ title to different cities around the world as did the WHO 2016 global urban ambient air quality database (WHO, 2016; 2018a).

Based on the 2018 WHO database, Wikipedia (2019) published a list of the 500 most polluted cities by PM$_{2.5}$ concentrations. CBS News (2019) similarly published a list of the fifty most polluted cities. Based on PM$_{2.5}$ data measured in 62 capital cities (2018), IQAir AirVisual (2019a) published an indicative ranking with New Delhi at the top, followed by Dhaka, Kabul, Manama, Ulaanbaatar, Kuwait City, Kathmandu, Beijing, Abu Dhabi, and Jakarta. The World Economic Forum (WEF) used the IQAir data to state that seven of the world’s ten most polluted cities are in India (WEF, 2019).

Based on the 2016 WHO database, the WEF published a similar list of the twenty most polluted cities in the world with respect to PM$_{10}$. Onitsha (Nigeria) was identified as the most polluted city followed by Peshawar and Rawalpindi (Pakistan), Zabol (Iran), Kaduna and Aba (Nigeria), Riyadh and Al Jubail (Saudi Arabia), Mazar-Sharif (Afghanistan), and Gwalior (India) (WEF, 2016). The other ten cities on the WEF worst polluted cities list were Hamad Town and Ma’ameer (Bahrain), Allahabad and Raipur (India), Shijiazhuang (China), Karachi (Pakistan), Damman, (Saudi Arabia), Umuahia (Nigeria), Kabul (Afghanistan), and Bosher (Iran).

The variation in these lists of most polluted cities within two years raises the question if it makes sense to award the ‘Most Polluted City’ title to different cities around the world (CNN, 2016a;b; WEF, 2016; HT, 2016; The Hindu, 2016; Gutnikunda, 2016; WP, 2016; TT, 2016; WSJ, 2016; Indianexpress, 2016a;b; Latimes, 2016; Livemint, 2016; MWN, 2016; NAIJ, 2016; Theguardian, 2016).

New Delhi Television (NDTV), in a similar consideration of the single-day air quality index (AQI) on 30 October 2019 stated that New Delhi was the most polluted city, followed by Lahore (Pakistan), Hanoi (Vietnam), Dhaka (Bangladesh), Hangzhou, Beijing and
Shenyang (China), Sofia (Bulgaria), Ulaanbaatar (Mongolia) and Kolkata (India) (NDTV, 2019). In contrast, a 2018 IQAir Air Visual report found that New Delhi ranked eleventh in the fifty most polluted cities, with six Indian cities (Gurugram, Faridabad, Bhiwadi, Noida, Patna, and Lucknow), two Pakistani cities (Faisalabad and Hotan). Hot (China) was ranked higher than New Delhi (IQAir Air Visual, 2019a). These different rankings based on different time durations of exposures clearly demonstrate the arbitrariness of make of a list of the most polluted cities.

While this “name and shame” approach (or refusal) may make eye-catching headlines, it can be inaccurate and misleading. Saying one city is more polluted than another is like comparing apples and pears, especially in the developing world. In addition, the pollutants that cause poor air quality in two cities may be very different. In the USA, The American Lung Association (ALA) characterized Los Angeles, California (CA) as the most polluted city with respect to ozone; Bakersfield, CA, was assessed to be the most polluted city, when it comes to short-term (24 hours) PM$_{2.5}$ concentrations while Fresno-Madera-Hanford, CA, was found to be the most polluted area with regard to long-term (annual) PM$_{2.5}$ averages (ALA, 2019). Martin et al. (2019) tried to put an end to ranking speculation by stating that nobody can know ‘which city has the highest concentration of particulate matter’.

This is not to say that we should not raise awareness of urban air pollution. It is a “silent killer” that can increase the risk of death and disease from chronic obstructive pulmonary disease (COPD) (43%), lung cancer (29%), ischaemic heart disease (25 %), deaths from stroke (24%), and death and disease from acute lower respiratory diseases (17%) (WHO, 2019a). Often the poor and vulnerable groups such as children and the elderly suffer the most (UN Environment, 2018; WHO, 2018b; UNICEF, 2018; Schröder et al., 2018; Patella et al., 2018; PAHO, 2018; Walker, 2012; Wright and Diab, 2011; WHO, 2010; Samet and White, 2004; Lipfert, 2004).

The 2018 WHO air quality database is an impressive piece of data compilation. It has PM$_{10}$ (fine PM of 2.5 microns or less in diameter) monitoring data for 3,570 cities in 97 countries, and PM$_{2.5}$ (fine PM of 2.5 microns or less in diameter) data for 2,628 cities in 81 countries, and is an impressive piece of data compilation.

The database uses PM data from established public air quality monitoring systems around the world. PM$_{10}$ and PM$_{2.5}$ include pollutants such as sulphates, nitrates and black carbon, which
penetrate deep into the lungs and into the cardiovascular system, posing the greatest risks to human health.

Unsurprisingly, the WHO found relatively low levels of urban air pollution in high-income (HI) countries (e.g. in Western Europe, the Americas, the Western Pacific, and Oceania) and high levels in low-and middle-income (LMI) countries (e.g. in Africa, Latin America, and Southeast Asia) and even in high-income countries in Latin America. In LMI countries, lack of funding and inadequate staffing are key barriers to effective air pollution reduction. The relatively low levels of urban air pollution in HI countries does not mean that people think their air is clean, but the link between public perception of and public response to air pollution is still weak (Oltra and Sala, 2015; 2014; Kelly and Fussell, 2015). In this paper, we discuss the challenges of comparing cities with respect to air pollution and then investigate the strengths and weaknesses of the WHO 2016 and 2018 databases with respect to several criteria. Finally, we make recommendations for improving future WHO air quality databases.

**Methodology**

The rationale for this paper is to examine the 2018 WHO global ambient air quality database and assess certain database properties. In particular, we examine the comparability of air quality data reported for different cities, the number of concentrations reported in the database versus the number of data existing at the time of WHO’s compilation. Most developed countries now have fully automated systems for urban air quality monitoring (UAQMon) with simultaneous visual display and an auto-transmittance facility. In contrast, UAQMon programmes in developing countries have severe resource and infrastructure constraints. Often such constraints are the main factor that determines the configuration of an air quality monitoring network to meet minimum local data needs. While UAQMon systems have to be designed to meet the objectives with available resources, essential criteria applied for UAQMon in developed countries have also to be applied for UAQMon in developing countries if air quality monitoring results are to be comparable. This paper will assess the WHO database on the following four essential criteria: (i) quality assurance and quality control (QA/QC); (ii) spatial representativeness; (iii) temporal representativeness; and (iv) meteorological conditions and topographic features.

*Quality Assurance and Quality Control*
Whatever the objectives – whether for health impact assessment, to meet local or national objectives, assessing traffic or industrial impacts, planning, policy development or providing public information - measurements will need to be accurate and reliable if they are to prove useful. Without QA/QC, measured data will not provide a sound basis for the assessment of population health effects of air pollution or for effective air quality management; as a result, any investment of money, time and effort made in monitoring will have been wasted. Proper QA/QC is essential in ensuring the comparability of measurements made at different monitoring sites. QA/QC is therefore a basic tool in ensuring that data within a network of sites are harmonised.

Spatial representativeness

Spatial representativeness relates to the question of where UAQMon is to take place. In cities, monitoring is usually undertaken at selected sites, rather than at points on a grid. Sites should be representative of specific location types covering, for example, characteristic central urban, industrial, residential, population-exposure, commercial or kerbside areas. UAQMon stations may differ from neighbouring urban sites affected by multiple sources. According to European Union (EU) Directive 2008/50/EC, at least two fixed monitoring stations shall be installed for a city with less than 250,000 inhabitants to measure the annual average of atmospheric PM and one more for every 250,000 inhabitants up to 1.5 million inhabitants; for up to 6 million inhabitants the directive recommends 13 sites and for urban areas with more than 6 million inhabitants 15 sites (EU 2008).

Temporal representativeness

The EC Directive 2008/50/EC suggests a minimum data capture of 90 per cent (EU 2008). WHO recommends that 50% of the valid data for the reported period should be available to obtain annual average values, and at least 75% of valid data should be available to obtain 1-hour average values from data with a smaller averaging time (WHO 1999).

Meteorological conditions and topographic features

Prevailing meteorological conditions and topographic features will strongly influence the dispersion of air pollutants and the production of secondary pollutants in the atmosphere. A city will have higher pollutant concentrations in a dry year than in a wet year. Different seasons (i.e. summer/winter) have unique meteorological conditions and activities (e.g. burning of agricultural residues) that may cause dips or spikes in pollution. If data for one
season are used to extrapolate an annual mean pollution level, the results may be skewed.

In addition to the four key criteria, we examine the comparability of air pollutant concentration data taken in different years and at different seasons among cities. Some cities generate most of their own air pollution (e.g. from road traffic) and can address the sources, while others are downwind from industrial areas or other external sources they cannot control. We look at the comparability of cities with different transboundary pollution regimes.

Monitoring methods used for pollutants in one city may differ from those in other cities, requiring adjustments to make the data comparable. Analysis of the data may also vary; some cities may eliminate outliers (very high or low values), while others include all data readings. Finally, we address the issue of pollutant selection in the WHO database and the conversion of PM$_{2.5}$ (PM$_{10}$) to PM$_{10}$ (PM$_{2.5}$) and if monitoring of only one of these particle ranges is monitored. Usually only few air pollutants are chosen for any given area considering their potential for adverse effects on human health, animals, natural vegetation, agricultural crops or the ecosystem. In general, it is necessary to first focus on those pollutants, for which air quality standards and guidelines.

**Strengths of the WHO databases**

The main strength of the 2016 and 2018 WHO air quality databases is that they attempt to provide a global overview of PM pollution. It compiles PM mass concentration data from over 4,300 cities globally, with most data from developed countries. Less than 28 per cent (approximately 1,200) are from developing countries. The database provides quantitative data on PM$_{10}$ (PM$_{2.5}$) concentrations, where measured, and estimates of PM$_{2.5}$ (PM$_{10}$) concentrations not measured, using PM$_{2.5}$/PM$_{10}$ conversion factors.

From the viewpoint of health, PM$_{2.5}$ and PM$_{10}$ are the most hazardous air pollutants. WHO estimates that most of the global mortality caused by air pollution is due to exposure to PM$_{2.5}$, with 91 per cent of 4.2 million premature deaths occurring in low- and middle-income countries (WHO, 2018c). The WHO review of evidence on the health aspects of air pollution has demonstrated (WHO, 2013) and a Health Effects Institute report on global air pollution has reiterated (HEI, 2019) that the annual mean concentrations of PM$_{2.5}$ and PM$_{10}$ are representative of long-term human exposure.
The data in the WHO 2016 and 2018 databases include measurements assessed for urban background, residential areas, commercial and mixed areas are used for averaging over urban sites, while ‘hot spot’ data or data from exclusively industrial areas/kerbside areas are excluded except in a few exceptional cases. For data to be included in the WHO 2018 database temporal coverage greater than six months was required and considered representative of a yearly measurement. Only few exceptions were allowed.

**Weaknesses of the WHO databases**

In this section we consider limitations already noted by WHO, other general limitations and specific limitations of the databases.

**Limitations noted by WHO**

In the 2016 and 2018 databases data from sites close to sources such as industries, power plants, highways, and urban kerbsides are not included. This is important in developing countries since many people are living near to and exposed to emission from such sites. Cities of inhabitants less than 100,000 are not included although the population may be exposed to emissions from industrial facilities outside the urban area.

Data from different countries have only limited comparability due to different locations; different measurement methods; different percentages of coverage of the year; and the fact that converted PM$_{2.5}$/PM$_{10}$ values are only indicative.

These are already substantial limitations why, in general, compiled air quality data of cities should be interpreted and not directly compared. Different locations of air quality monitoring sites among cities or within a city will affect the spatial representativeness of data. A city of a certain size will need a minimum number of monitoring stations in order to obtain spatially representative air pollutant concentrations. Monitoring stations need to be situated in such a way that they ensure coverage and are representative of urban air quality levels.

However, the actual placement of stations can vary. They may be concentrated in (less-polluted) residential areas in one city, and on busy roads (with high pollution) in another.

Different measurement methods for PM concentrations include gravimetric, optical and oscillating microbalance methods (Amaral et al., 2015). The gravimetric method is based on
filters and cascade impactors and can collect particles and estimate their mass concentrations. Optical methods used for estimating particle mass concentrations, in real time, are based on the principles of light scattering, absorption, and extinction.

Oscillating microbalances measure changes in the oscillating frequency of a crystal or filter on which particles are sampled and translate the change of the frequency into the mass collected. All these measurement methods have different specifications such as detection limit, particle size range, accuracy and precision (Amaral et al., 2015). In particular, measurements from different instruments that do not measure particle mass directly are not always equivalent or comparable, as is demonstrated by the need for a correction formula between a light-scattering instrument such as the DustTrak and the Tapered Element Oscillating Mictobalance (Morawska et al., 2003). This fact makes comparisons of PM concentration among cities problematic.

In addition, background pollution related to transboundary movement of air pollutants also complicates any attempt of city comparison. Some cities generate most of their own air pollution (e.g. from road traffic) and can readily address the sources, while others are downwind from industrial areas or other external sources they cannot control. An example is Hong Kong, which suffers from transboundary pollution emerging in the Pearl River Delta (GovHK, 2015).

A city may not measure air pollution at all. A city that does not monitor may have higher air pollutant concentrations than another city that monitors its air quality – but because the former is not in the database, it will not make a “most polluted” list. For example, an analysis by the Russian Service for Hydrometeorology and Environmental Monitoring (RSHEM) of air quality in Russian cities estimated the grade of air pollution based on indicators (Klyuev, 2019). These indicators included hazardous emissions from stationary and mobile sources, the air pollution potential based on meteorological factors, and the frequency cities appeared on the RSHEM blacklists (Klyuev, 2019). Since indicators do not quantitatively represent air quality concentration levels, extremely high PM concentration may still occur in the Russian cities considered.

Different percentages of temporal coverage during a year raises important issues related to the minimum number of valid observations, the influence of dry and wet years, and seasonal
influences. Each monitoring station must have a minimum of valid observations per year, for example, 75 per cent, in order to achieve concentration averages representative for a year.

A city will have higher pollutant concentrations in a dry year than in a wet year. Therefore, data taken in different years in different cities are not comparable. A city labelled the ‘most polluted’ based on 2013 data may not achieve the same ranking with 2015 data due to meteorological variation. Also, different seasons (i.e. summer/winter) have unique meteorological conditions and activities (e.g. burning of agricultural residues) that may cause dips or spikes in pollution. If data for one season are used to extrapolate an annual mean pollution level, the results may be skewed.

Other limitations - general

WHO data are limited to annual averages of PM$_{2.5}$ and PM$_{10}$ which are related to long-term health effects of PM pollution i.e. 4.2 million premature deaths per year globally (WHO, 2019b). Short-term health impacts of PM are not covered by annual averages of PM concentrations.

The Global Burden of Disease (GBD) study has attributed 233,638 premature deaths per year globally to long-term exposure to ozone (O$_3$) (Cohen et al., 2017; GBD 2016 Risk Factor Collaborators, 2017). Although a global estimate of premature deaths due to exposure to nitrogen dioxide (NO$_2$) does not to exist, some papers have estimated the premature deaths attributable to NO$_2$ (EEA, 2019; Abdolahnejad et al., 2018; Hadei et al., 2017; Walton et al., 2015). The European Environment Agency (2014) estimated a total of 78,000 premature deaths from exposure to NO$_2$ in forty-one European countries. In a study of PM$_{2.5}$ and NO$_2$ related premature deaths in London, 5,900 premature deaths (2010) across London was found to be associated with NO$_2$ long term exposure, while the premature deaths associated with long-term exposure to PM$_{2.5}$ were 3,500 (Walton et al., 2015).

As a consequence, the WHO databases should also include NO$_2$ and O$_3$ data. This was the case in the UNEP/WHO Global environment Monitoring System for Air (GEMS/Air) database (1975-1996), and in the collection of the Healthy Cities Air Management Information System (AMIS) (1997-2003) (Schwela, 1999). In addition, the omission of short-
term exposure data for PM and gaseous compounds is also a shortcoming of the WHO 2016 and 2018 databases as compared to GEMS/Air and AMIS databases.

In some developing countries such as Azerbaijan (Baku) only total suspended particulate matter (TSP) concentrations are monitored, the inclusion of which would probably give an indication on the population exposure as is demonstrated by the calculated annual mean PM$_{10}$ concentrations (using a TSP/PM$_{10}$ ratio of 1.35) for 2005-2013 in Baku from the EC supported National Pilot Project - Azerbaijan (REC, 2014). Although exposure-response relationships are not developed for TSP exposure, the WHO TSP guideline values (WHO, 1979; 1987, never repealed) can be used for a qualitative judgement on the health effects due to TSP exposure. The WHO databases are limited to concentrations only and do not assess the at-risk groups such as those under 18, those aged 65 and over, and those suffering from asthma, chronic obstructive lung disease, and lung cancer, cardiovascular disease, diabetes, and those having a low socio-economic status.

In contrast, the American Lung Association (ALA) has considered these at-risk groups since 2012 (ALA, 2019). The ALA estimates the number of people who live in areas that have unhealthy levels of either O$_3$ or PM pollution; the number of people who suffer from unhealthy year-round levels of PM pollution; and others with short-term exposure of PM and those with exposures to short-term, year-round PM and O$_3$.

A general limitation of the WHO databases is the uncertainty associated with how stakeholders (e.g., politicians, media, others) will use the data. In particular, misinterpretation of the data by the media, international organizations, and others that rank cities according to their pollution. This use of incomparable data is counterproductive, misleading and inept and does not give incentives to politicians and decision makers for good governance on air quality management.

**Other specific limitations**

In the following section some specific issues of the WHO 2018 database are addressed, regarding the incompleteness of the database despite the availability of air quality measurements; the elimination of hot spot data, QA/QC; spatial and temporal representativeness; and the conversion of PM$_{2.5}$ and PM$_{10}$ data if only one of the size distributions are monitored and the other estimated by using a PM$_{2.5}$/PM$_{10}$ ratio.
Firstly, a few examples for PM are given that could have been included in the WHO 2018 database because they were published before the time of its publication in May 2018. These include air quality data for Argentina, Brunei Darussalam, Egypt, Ghana, India, Kuwait, Malaysia, Nigeria, Kazakhstan, the Russian Federation, Ukraine, and Taiwan.

**Argentina**

For Argentina, the WHO database reports PM$_{10}$ concentration data from only three monitoring stations in Buenos Aires (Parque Centenario, Córdoba, La Boca) and it uses a PM$_{2.5}$/PM$_{10}$ ratio (0.44) for estimating PM$_{2.5}$ concentrations (BAC, 2019a; b; c). It should be noted that this ratio relies on educated guesswork (see below) since a study (Riojas-Rodriguez et al., 2016) infers a range of PM$_{2.5}$/PM$_{10}$ ratios for nineteen Latin American cities to lie between 0.23 and 0.89 for Jalisco (Mexico) and San José, (Costa Rica), respectively.

Other monitoring stations exist in Argentinian cities and have produced PM$_{10}$ data since the late 1990s. For example, since 1997 Bahia Blanca has monitored PM$_{10}$ (and some gaseous compounds) (Allende et al., 2010). This PM$_{10}$ data has been validated up to 2013 and the Bahia Blanca government has published data for 2010 to 2012 (GABB, 2019). Real time air quality indices (AQI) are published daily at [https://aqicn.org/city/argentina/bahia-blanca/](https://aqicn.org/city/argentina/bahia-blanca/).

Two monitoring sites exist in Acumar (La Matanza and Dock Sud I) in the vicinity of Buenos Aires that monitor PM$_{10}$ and PM$_{2.5}$, and reports daily AQI (BAAP, 2019).

**Brunei Darussalam**

Brunei Darussalam has established four stations that are located throughout the four districts (Brunei Muara, Temburong, Tutong, Belait) that continuously monitoring PM$_{10}$ and PM$_{2.5}$ (UNEP, 2015; AP Brunei, 2019). PM monitoring stations have been in operation in Brunei since the 1990s (Radojevic and Hassan, 1999; UNEP/APCAP/CCAC, 2019). The WHO database reports no PM data for Brunei.

**Egypt**

Egypt has 88 fixed air quality monitoring stations countrywide and two mobile monitoring units, with 42 real-time continuous monitoring stations and 46 air pollutant sampling stations in 2016 (Mourad, undated; EEEA, 2016). Of the 88 monitoring and sampling stations 49, 13, 8, 15, and 3 are located in Cairo, the Delta, Alexandria, Upper Egypt, and on
the Sinai peninsula, respectively. All monitoring stations measure PM$_{10}$ and criteria gaseous pollutants. Data are reported monthly and compiled in annual reports. In the 2018 WHO database there are only data from 18 urban stations in the Delta Region and Alexandria and 13 stations for Greater Cairo are aggregated. The Delta Region is a conglomerate of different smaller and larger urban areas of varying sizes. It is therefore inappropriate to compare a conglomerate of secondary cities and Alexandria with a megacity such as Cairo.

**Ghana**
Ghana, through its Environmental Protection Agency, operates an air quality monitoring network that collects PM$_{10}$ and limited PM$_{2.5}$ data from up to 15 locations throughout the city of Accra and its environs (Ghana EPA, 2018). PM$_{10}$ concentrations have been assessed since 2005 at ten roadside monitoring sites, two in industrial and residential areas and one in a commercial area; PM$_{2.5}$ is measured at one station (Ghana EPA, 2017). This station has PM$_{10}$ and PM$_{2.5}$ monitoring data for eleven years (Apoh, 2018). Data are missing for 2011-2013 but data up to the year 2017 were available at the time of the publication of the WHO 2018 database.

**India**
The WHO 2018 database for India presents PM$_{2.5}$ and PM$_{10}$ concentration data for 2015/2016 for 34 cities. For 101 cities PM$_{10}$ concentration values are reported for 2012 and a few ones for the years 2013-2015. Compared to the data reported by the Indian government on the internet, the WHO data are incomplete. The Indian Central Pollution Control Board (CPCB) manages a National Air Quality Monitoring Programme (NAMP), which manually collects, among other air pollutants, samples of PM$_{10}$ and PM$_{2.5}$ twice a week for 8-hours within 24 hour periods (Pant et al., 2018; CPCB, 1919 a; b; c). The number of cities and sampling stations for each State are compiled in the Supplement as Table S1 for PM$_{10}$ for 2013 to 2016 and Table S2 for PM$_{2.5}$ for 2014-2016. According to Table S1, PM$_{10}$ was monitored in 2013, 2014, 2015 and 2016 in 223, 234, 241 and 250 cities, respectively. PM$_{2.5}$ was monitored in 2014, 2015 and 2016 in 29, 59 and 71 cities, respectively. These data are much more recent than those reported in the WHO database and the city numbers contrast distinctly to the 101 cities in the WHO database cited above. In this discussion, the challenges of the manual PM monitoring in India, especially the reduced monitoring duration but also other methodological issues should be kept in mind (Pant, 2019; Verma, 2019).
In addition to the monitoring sites under the NAMP, several States (including Maharashtra, Gujarat, Kerala, Odisha, Karnataka, Telangana and Andhra Pradesh) conduct outdoor PM monitoring at additional sites under a State Ambient Air quality Monitoring Programme (SAMP), the results of which do not appear to be included in the WHO database except for Karnataka. The CPCB has also set up a network of continuous automatic air quality monitoring stations (CAAQMS) for assessing PM$_{10}$ and PM$_{2.5}$.

In September 2018, there were 65 cities monitored at more than 130 sites (Patna, 2019) and as of November 2019 the number of cities increased to 101 with 161 monitoring stations (https://app.cpebcr.com/ccr_docs/caaqms_list_All_India.pdf). From the increase in the number of monitoring stations it is possible that in 2016 more cities in India had automatic stations than those listed in the WHO 2018 database.

**Malaysia**

Malaysia has established a National Air Quality Monitoring network of six real-time PM$_{10}$ monitoring stations (Continuous Air Quality Monitoring, CAQM), which is supplemented by 19 sites of the Manual Air Quality Monitoring (MAQM) network. The MAQM network measures PM$_{10}$ and TSP once in every six days (MESTECC, 2019). The 2018 WHO database quotes PM$_{10}$ data from only six cities, apparently from the CAQM network, and no data from the MAQM network, and does not include the capital, Kuala Lumpur.

**Nigeria**

Data from 12 cities in Nigeria were presented in the 2016 database and Onitsha was reported to have the extreme PM$_{10}$ concentration of 594 µg/m$^3$ (2009), a value which is neither spatially representative for the city (six monitoring stations would be necessary instead of only one existing) nor temporally representative for a year (data coverage only 4 percent). None of them is in the 2018 database and no reason is provided for this omission of the Nigerian data. At least data from Port Harcourt should be included since they are available in the literature (Akinfolarin, 2017; Ede and Edokpa, 2015).

**Kazakhstan**

Kazakhstan has only one continuously monitoring site in Astana at the United States Embassy, which monitors PM$_{2.5}$. The embassy emphasises that data from a single monitoring station cannot be applied to an entire city (US Embassy Kazakhstan, 2019; AP_Kazakhstan,
2019). No data is reported in the WHO 2018 database. Much more data on PM than reported in the WHO 2018 database exist.

**Russian Federation**

In 2013, eight PM$_{10}$ automatic monitoring stations and two PM$_{2.5}$ continuously monitoring stations were operating in Moscow. (Kislova, 2013). PM$_{10}$ annual average concentrations were reported for the period 2003 to 2012. The WHO 2018 database presents data for two urban background stations in Moscow for the year 2009.

**Taiwan**

Seventeen cities in Taiwan perform air quality monitoring and measure PM$_{2.5}$ and PM$_{10}$, among other compounds (EPA Taiwan, 2019). These data are not quoted in WHO’s databases. Although this omission is probably due to the controversial issue of the political status of Taiwan, it is the opinion of the authors that air quality data from Taiwanese cities have nothing to do with a recognition of Taiwan as a sovereign state and, therefore, should have been included in the WHO database.

**Ukraine**

Since the 1990s, the Ukraine has monitored only PM in terms of TSP. In 2020, Ukraine had 33 real-time PM$_{10}$ and PM$_{2.5}$ urban monitoring stations, some of these were in operation in 2016 (AP_Ukraine, 2019; Milinevski et al., 2018). IQAir Air Visual ranks ten Ukrainian cities by US AQI for PM$_{2.5}$ (IQAir Air Visual, 293 2019b). The WHO database quotes no data on PM$_{2.5}$ and PM$_{10}$.

**Hot spot data**

A second issue with respect to the WHO databases is the elimination of hot spot data or their consideration only in specific situations. In the Notes to the WHO database it is stated that monitors “are not unduly influenced by a single source of pollution … rather the monitors should reflect exposures over a wide area”. This limitation may be appropriate in cities of developed countries, where city street are wide and well ventilated, and people are exposed to emissions from transport for a short time. However, this limitation may be inappropriate in cities of developing countries where street vendors spending up to 12 hours at kerbside and are exposed to vehicle emissions and air pollutants from industrial and other sources (Kongtip et al., 2008; Serya et al., 2019).
This may also apply to people living close to highly polluted streets and roads in developed countries, who are exposed to traffic-related air pollution, which may cause the onset of childhood asthma, impaired lung function, premature death and death from cardiovascular diseases and cardiovascular morbidity (HEI, 2010; ALA, 2018). A Danish study found that long-term exposure to traffic air pollution may increase the risk of asthmatics and people suffering from diabetes or developing chronic obstructive pulmonary disease (Andersen et al., 2011).

QA/QC

The third and most important issue refers to the quality of the data in the WHO database with regard to QA/QC. Whatever the objectives reported measurements will need to be accurate and reliable if they are to prove useful. This is why QA/QC is a key component of any air quality monitoring programme. Proper QA/QC is also essential in ensuring the comparability of measurements made at different monitoring sites. QA/QC is therefore a basic tool in ensuring that data within a network of sites are harmonised.

A properly designed and implemented QA/QC programme should cover all aspects of network operation, ranging from system design and site selection through equipment selection, operation, calibration and maintenance to data management and validation. Essentially, QA refers to the overall management of the entire process leading to a defined quality of the data product; quality control refers to the activities undertaken to obtain a specified accuracy and precision of the measurement. QA functions will cover directly measurement-related activities including network operation, calibration, data handling, review and training.

There is no indication in the Notes of the 2018 WHO database that issues of QA/QC were addressed in the compilation of data. While WHO certainly cannot check the validity of the collected data, questions following from the presentation of QA/QC requirements on the application of rigorous QA/QC procedures should be answered by the data providers.

The GAP Forum Air Pollution Monitoring Manual provides examples of the main questions that should be answered by data providers (Schwela, 2011). An example for data where QA/QC requirements were neglected is the case of data from Bosnia and Herzegovina where
monitoring is performed in 17 (only 7 quoted in the WHO 2018 database) urban areas (FHMI, 2017; RHMI, 2018). As a result, such data are of unknown quality and not necessarily suited for city comparison.

Spatial and temporal representativeness

Related to the issue of QA/QC is the need for spatial and temporal representativeness. Table 1 shows the number of monitoring stations needed for a given urban population of cities in a number of countries and compares them with the numbers of monitoring station quoted in the WHO 2018 database. The table indicates that the number of monitoring stations in the WHO database are below the minimum number required by EU Directive 2008/50/EC according to population size. Therefore, the results reported in the WHO database cannot be considered as spatially representative for the cities. An exception appears to be Gyeonggi (South Korea). Gyeonggi, however, is not a city but a South Korean province, consisting of 24 cities of different population sizes (MoE, 2013). This makes a comparison of Gyeonggi with other cities problematic.
| Country     | City         | Year of monitoring or reporting | Number of monitoring stations (WHO, 2018) | Population[million] | Minimum number of stations (EU, 2008) |
|-------------|--------------|----------------------------------|------------------------------------------|---------------------|--------------------------------------|
| Chile       | Santiago     | 2016                             | 1                                        | 4.65                | 11                                   |
| Cameroon    | Bamenda      | 2012                             | 1                                        | 0.22                | 3                                    |
| Chile       | Puente Alto  | 2016                             | 1                                        | 0.49                | 2                                    |
| Saudi Arabia| Riyadh       | 2016                             | 1                                        | 4.08                | 11                                   |
| Pakistan    | Peshawar     | 2010                             | 1                                        | 2.98                | 10                                   |
| Poland      | Warsawa      | 2016                             | 7                                        | 1.76                | 7                                    |
| Macedonia   | Tetovo       | 2013                             | 1                                        | 0.05                | 2                                    |
| India       | Gwalior      | 2012                             | 2                                        | 0.82                | 4                                    |
| Korea       | Gyeonggi     | 2014                             | 71                                       | 12.3                | 15                                   |
| China       | Shijiazhuang | 2015                             | 1                                        | 10.7                | 15                                   |
| China       | Xingtai      | 2016                             | 1                                        | 7.10                | 15                                   |
| Country   | City    | Year | Data Coverage | Annual PM Value | Temporal Representativeness |
|-----------|---------|------|---------------|-----------------|-----------------------------|
| Iran      | Zabol   | 2016 | 1             | 0.13            |                             |
| Brazil    | Santos  | 2016 | 2             | 0.43            |                             |
| Peru      | Lima    | 2016 | 3             | 8.85            | 15                          |
| Malaysia  | Kuching | 2014 | 1             | 50.83           |                             |

Temporal representativeness

Temporal representativeness of values is also an important issue when estimating annual PM values. As discussed above, a minimum number of data should be available for the estimation of annual mean PM concentration, for example, 75 per cent or even 90 per cent. Lower percentages risk biased estimates of an annual mean. When investigating if any of these requirements are fulfilled in the WHO database instances are found where this is not the case. For example, PM$_{2.5}$ monitoring in Bamenda (Cameroon), was performed seven times per week for 24 hours during two weeks, corresponding to data coverage of 4 per cent (Antonel and Chowdhury, 2014). Other examples lacking temporal representativeness include Peshawar (Pakistan), where monitoring was performed for half the week, corresponding to data coverage of 1 per cent (Alam et al., 2011) and Gwalior (India), where monitoring at two stations was performed during 15 and 19 days, corresponding to data coverage of between 4 and 5 per cent, respectively (GoI-OGD, 2012). Such low data coverage should not be considered temporally representative for a year as claimed in the WHO database for Bamenda and Gwalior. Another example from the WHO 2016 database is Onitsha, (Nigeria). PM$_{10}$ monitoring was performed once per week for 12 hours during 36 weeks (Ngele and Onwu, 2015). This corresponds to data coverage of 5 per cent far below the 75 per cent usually required. Such low data coverage should not be considered temporally representative for a year.

PM$_{2.5}$/PM$_{10}$ conversion factors

A final issue of concern is the use of PM$_{2.5}$/PM$_{10}$ conversion factors if only one of the size of PM distribution is monitored. If a local PM$_{2.5}$/PM$_{10}$ factor is unknown, the usual approach of
WHO to the problem is to use a region specific conversion factor. For developing countries the selected conversion factor is often around 0.5 (WHO, 2008). In the WHO 2018 database data conversion from measured PM$_{2.5}$ (PM$_{10}$) to converted PM$_{10}$ (PM$_{2.5}$) is sometimes performed when PM$_{10}$ (PM$_{2.5}$) measurements exist, for example, US and Indian cities. As Table 2 shows, estimated conversion PM$_{2.5}$/PM$_{10}$ ratios can and often differ from the monitored ones.

**Table 2:** PM$_{2.5}$/PM$_{10}$ conversion factors for various cities in the USA and India.

| City                  | PM$_{2.5}$/PM$_{10}$ measured | PM$_{2.5}$/PM$_{10}$ converted (WHO) |
|-----------------------|-------------------------------|--------------------------------------|
| Bakersfield, CA, USA  | 0.34                          | 0.49                                 |
| Baton Rouge, LA, USA  | 0.46                          | 0.45                                 |
| Boston, MA, USA       | 0.55                          | 0.50                                 |
| Chicago, IL, USA      | 0.37                          | 0.55                                 |
| New York, NY, USA     | 0.59                          | 0.50                                 |
| Washington DC, USA    | 0.51                          | 0.47                                 |
| Surat, India          | 0.34                          | 0.54                                 |
| Vadodara, India       | 0.32                          | 0.54                                 |
| Vapi, India           | 0.31                          | 0.54                                 |
| Indore, India         | 0.57                          | 0.53                                 |
| Nagda, India          | 0.52                          | 0.53                                 |
| Rayagada, India       | 0.58                          | 0.54                                 |
| Rourkela, India       | 0.60                          | 0.53                                 |
| Sambalpur, India      | 0.65                          | 0.53                                 |
| Coimbatore, India     | 0.59                          | 0.53                                 |
| Nagonda, India        | 0.56                          | 0.54                                 |
| Howrah, India         | 0.58                          | 0.54                                 |
| Singrauli, India      | 0.51                          | 0.53                                 |
| Ujain, India          | 0.49                          | 0.54                                 |

**Conclusion and recommendations**
Clean air is a basic human right, and we urgently need to act to reduce air pollution – particularly in developing-country cities where poor air quality poses a significant threat to human health and wellbeing. Rankings and comparisons that single out the “worst” do not advance this cause but instead confuse people and politicise a public health issue. If we are to save lives now and protect future generations, we need to be more thoughtful and precise when we talk about urban air quality.

The WHO air quality databases are attempts to gain an overview of the state of air quality in cities around the world. This is important to raise awareness, measure progress and to inspire action. However, compiling database of comparable air quality from cities is not without challenges as demonstrated here. These include monitoring versus. non-monitoring, representativeness, data coverage, background pollution, meteorological condition, seasonal monitoring, issues of different monitoring methodologies and QA/QC. The Notes in the WHO global air quality databases should clearly advise the users, in particular the media, against comparing and ranking cities as this is misleading. There are also political consequences: if city officials fear being “named and shamed”, they have a strong incentive to hide their data or under-report pollution. The controversy over Beijing’s air quality data highlights these risks (Guardian, 2014) as well as the removal of the Nigeria data from the 2018 database. The general and specific limitations demonstrated in this paper result in the strong recommendation that WHO’s global ambient air quality database would benefit from peer review to minimise its limitations as far as possible.

In order to improve future WHO databases and have comprehensive and reliable data, it is recommended that data collection be accompanied by a rigorous review of the existing literature; that annual means for NO₂ and O₃ are also compiled as was the case in the WHO Healthy Cities AMIS database; that data providers are requested to answer a certain set of questions with respect to QA/QC of their data such as following rigorously a detailed QA/QC plan. This would ensure the comparability of measurements, assessment of the accuracy and precision of data and that monitoring results meet defined standards with a stated level of confidence. Finally, a strong warning should be given to data users including the media to not abuse the data to name and shame the “most polluted city”.

Acknowledgement: The authors wish to thank Dr Bjarne Sivertsen for hisa fruitful discussions
on the issues of this paper.

**Conflicts of interest:** The authors confirm that there are no conflicts of interest.

**Funding:** None

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| State                  | 2013 Number of Cities | 2014 Number of Monitoring Stations | 2015 Number of Monitoring Stations | 2016 Number of Monitoring Stations |
|------------------------|-----------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Andhra Pradesh         | 25                    | 48                                | 14                                | 24                                |
| Arunachal Pradesh      | -                     | 2                                 | 2                                 | -                                 |
| Assam                  | 13                    | 22                                | 13                                | 22                                |
| Bihar                  | -                     | 1                                 | 2                                 | 2                                 |
| Chandigarh             | 5                     | 12                                | 1                                 | 5                                 |
| Chattisgarh            | -                     | 4                                 | 7                                 | 8                                 |
| Dadra & Nagar Haveli   | 1                     | 1                                 | -                                 | 1                                 |
| Daman & Diu            | -                     | -                                 | -                                 | 1                                 |
| Delhi                  | 1                     | 10                                | 1                                 | 10                                |
| Goa                    | 16                    | 16                                | 17                                | 17                                |
| Gujarat                | 7                     | 19                                | 7                                 | 19                                |
| Haryana                | 3                     | 3                                 | 2                                 | 3                                 |
| Himachal Pradesh       | 10                    | 20                                | 11                                | 21                                |
| Jammu & Kashmir        | 1                     | 3                                 | 1                                 | 3                                 |
| Jharkhand              | 5                     | 5                                 | 4                                 | 6                                 |
| Karnataka              | 14                    | 25                                | 16                                | 26                                |
| Kerala                 | 11                    | 22                                | 11                                | 24                                |
| Lakshwadeep            | -                     | -                                 | -                                 | 1                                 |
| Madhya                 | 8                     | 17                                | 9                                 | 22                                |
| Pradesh          | 21 | 68 | 22 | 68 | 22 | 67 | 22 | 68 |
|------------------|----|----|----|----|----|----|----|----|
| Maharashtr a     |    |    |    |    |    |    |    |    |
| Manipur          | -  |    |    |    |    |    | 1  | 1  |
| Meghalaya        | 6  | 7  | 6  | 7  | 8  | 8  | 7  | 8  |
| Mizoram          | 4  | 11 | 4  | 11 | 4  | 11 | 4  | 11 |
Table S1: Number of cities and PM$_{10}$ monitoring stations in various States of India, 2013-2016

| State       | Number of cities | Number of monitoring stations | Number of cities | Number of monitoring stations | Number of cities | Number of monitoring stations | Number of cities | Number of monitoring stations |
|-------------|------------------|-------------------------------|------------------|-------------------------------|------------------|-------------------------------|------------------|-------------------------------|
| Nagaland    | 2                | 4                             | 2                | 4                             | 2                | 4                             | 2                | 4                             |
| Orissa/Odisha | 13             | 31                            | 14               | 32                            | 13               | 31                            | 14               | 34                            |
| Punjab      | 12               | 24                            | 14               | 27                            | 13               | 27                            | 11               | 24                            |
| Puducherry  | 1                | 3                             | 2                | 8                             | 2                | 6                             | 2                | 6                             |
| Rajasthan   | -                | -                             | -                | -                             | -                | -                             | -                | -                             |
| Sikkim      | -                | -                             | -                | -                             | -                | -                             | -                | -                             |
| Tamilnadu   | 8                | 30                            | 8                | 30                            | 8                | 31                            | 8                | 31                            |
| Telangana   | -                | -                             | -                | -                             | -                | -                             | -                | -                             |
| Uttar Pradesh | 23          | 57                            | 17               | 49                            | 17               | 52                            | 19               | 61                            |
| Uttarakhand | -                | -                             | -                | -                             | -                | -                             | -                | -                             |
| West Bengal | 8                | 18                            | 8                | 18                            | 8                | 16                            | 9                | 37                            |
### Table S2: Number of cities and PM$_{2.5}$ monitoring stations in various States of India, 2014-2016

| State                    | 2014 Number of Cities | 2014 Number of Monitoring stations | 2015 Number of Cities | 2015 Number of Monitoring stations | 2016 Number of Cities | 2016 Number of Monitoring stations |
|--------------------------|-----------------------|------------------------------------|-----------------------|------------------------------------|-----------------------|------------------------------------|
| Chandigarh               |                       |                                    |                       |                                    |                       | 1                                  |
| Chattisgarh              |                       |                                    |                       |                                    |                       | 5                                  |
| Dadra & Nagar Haveli     |                       |                                    |                       |                                    |                       | 1                                  |
| Daman & Diu              |                       |                                    |                       |                                    |                       | 1                                  |
| Delhi                    |                        1 |                                    |                        6 |                                    |                        1 |                                    | 7                                  |
| Goa                      | 1                      |                                    | 4                     |                                    | 14                    | 8                                  |
| Gujarat                  | 8                      |                                    | 19                    |                                    | 7                     | 13                                 | 22                                 |
| Karnataka                | -                      |                                    | -                     |                                    | 1                     | 1                                  | 6                                  |
| Madhya Pradesh           | 1                      |                                    | 2                     |                                    | 8                     | 14                                 | 2                                  | 75                                 |
| Maharashastra            | -                      |                                    | -                     |                                    | 1                     | 1                                  | -                                  |
| Orissa/Odisha            | 4                      |                                    | 12                    |                                    | 1                     | 3                                  | 31                                 | 1                                  | 2                                  |
| Tamilnadu                | -                      |                                    | -                     |                                    | -                     | -                                  | -                                  |
| Telangana                | Web: 1                |                                    | Web: 1               |                                    | -                     | -                                  | -                                  |
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| West Bengal              | -                      |                                    | -                     |                                    | -                     | -                                  | -                                  |

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