Air Pollution Monitoring Strategies and Technologies for Urban Areas

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Abstract Current ambient air quality monitoring is solely based on fixed monitoring sites, not always reflecting the exposure and effects on humans. This article reviews the current situation in Europe, the USA and Asia and discusses the main differences and similarities. Based on the analysis of the relation between monitoring techniques and strategies as well as the analysis of current trends and developments in monitoring strategies, new concepts and directions of future urban monitoring networks and strategies are presented and discussed.

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Contents

1 Introduction

Current strategies for monitoring urban air pollution arise from the abundant evidence of the harm that air pollution causes to human health (see the extensive review in [1]) and the broader environment. Types of harm include the acidification of soils and water [2, 3], eutrophication [4], and the erosion and soiling of buildings and structures (e.g. [5]). Globally air pollution may have both positive and negative effects including significant climatic implications [6] and their role as an important source of essential nutrients and minerals, e.g. for the Amazon region in South America [7]. The strategy chosen for air quality monitoring depends on the impact to be monitored, as well as on the available measurement techniques and financial considerations.

For example, monitoring long range transport of pollutants for the purpose of assessing eutrophication and acidification led to the set-up of the European Monitoring and Evaluation Programme [8] in 1979. The focus on investigating long range transport of acidic substances led to EMEP establishing remote background sites in Europe and standardised measurements for, e.g. sulphate and nitrate in particles and rainwater. This monitoring combined with modelling allows trans-boundary transport of these pollutants to be assessed and reduction measures to be established.

The main rationale for ambient air quality monitoring in urban areas concerns the negative health effects of pollutants on humans. The linkage between air pollutants and health effects has been established for many decades, though evidence from urban air pollution effects became most infamously known by the assessment of the London smog episode in 1952 [9]. This event and other investigations published before and afterwards lead to the establishment of legislations to improve ambient air quality. Table 1 gives an example of the development of air quality-related regulations in the UK and the European Union.

All air quality-related legislation is based on the presumption of a direct line connecting emissions, ambient air quality, exposure, uptake, dose and effect. Pursuing this idea, regulation starts at the point of emission. Whilst the emissions

Table 1 History of air pollution in the UK (based on [10])

Year and legislation	Focus/purpose
1273	Use of coal prohibited in London as being "prejudicial to health"
1306 – Royal Proclamation	Prohibiting craftsmen from using sea-coal in their furnaces
1845 – Railway Clauses Consolidated Act	Required railway engines to consume their own smoke
1847 – The Improvement Clauses Act	Contained a section dealing with factory smoke
1863 – Alkali, etc. Works Regulation Act	Required that 95% of the offensive emissions should be arrested
1866 – The Sanitary Act	Empowered sanitary authorities to take action in cases of smoke nuisances
1875 – The Public Health Act	Contained a section on smoke abatement from which legislation to the present day has been based
1946	First smokeless zone and prior approval legislation
1956 – Clean Air Act	Introduced smoke control areas, controlled chimney heights
1970 – EC Directive 70/220/EEC	Air pollution measures against gases from positive ignition engines of motor vehicles (emissions of CO and hydrocarbons)
1972 – EC Directive 72/306/EEC	Measures against diesel engine emissions limiting black smoke emissions from heavy duty vehicles
1974 – Control of Pollution Act	Regulation of motor fuels. Limits amount of sulphur in fuel oil
1975 – EC Directive 75/716/EEC	Sulphur content of certain liquid fuels. Amended in 1987 EC Directive 87/219/EEC: (1) The motor and oil fuel
1978 – EC Directive 78/611/EEC	Lead content of petrol limited to 0.4 gl^{-1}
1979 – International Convention on Long Range Transboundary Pollution	Introduced to control the transboundary effects of acid rain and to limit emission of acidifying pollutants
1980 – EC Directive 80/779/EEC	Air quality limit values and guide values for sulphur dioxide and suspended particles
1982 – EC Directive 82/884/EEC	Limit value for lead in the air
1984 – Directive 84/360/EEC	Common framework directive on combating pollution from industrial plants
1989 – EC Directive 89/427/EEC	Limit values and guide values of air quality for sulphur dioxide and suspended particulates. Harmonised measurement methods
1990 – Environmental Protection Act	Smaller emission sources under air pollution control by local authorities for the first time
1991 – The Road Vehicles Regulations	Set standards for in service emissions of CO and hydrocarbons to be included in the MOT test
1992 – EC Directive 92/72/EEC	Harmonised procedure for monitoring, exchange of information and public warnings for ozone
1995 – The Environment Act	New statutory framework for local air quality management with obligation to publish a National Strategy
1996 – EC Directive 96/62/EC	Framework for controlling levels of SO_2, NO_2, particulate matter, Pb, O_3, benzene, CO and other

(continued)

Table 1 (continued)

Year and legislation	Focus/purpose
	hydrocarbons leading to Daughter Directives 1–4: 1999/30/EC, 2000/69/EC, 2002/3/EC and 2004/107/EC
1997 – The National Air Quality Strategy	Published with commitments to achieve new air quality objectives throughout the UK by 2005
2008 – EC Directive 2008/50/EC	Merges existing legislation into one directive (excl. 4th daughter directive), sets new objectives for PM2.5 (fine particles) including the limit value and exposure-related objectives, and gives possibility to discount natural sources of pollution

from large industrial sources can be measured directly, the sheer multitude of individual air pollution sources (e.g. cars on the road or home heating systems) means that they cannot be assessed individually and instead regulatory assessment is extended to the measurement of ambient air quality. Emission monitoring, even though not the focus of this article, is hence intrinsically linked to ambient air quality monitoring to ensure that ambient limit values are achieved and allow efficient abatement strategies for air quality improvements when needed.

Extending the ideas of Chen et al. [11], the purpose of ambient air quality monitoring in urban areas can be described as:

1. Determining whether legal limit or target values are met at the monitoring sites
2. Deriving population-exposure-related values for health impact assessments
3. Providing information to check emissions inventories and pollutant evolution, allowing effective abatement strategies to be planned and executed
4. Providing real-time information allowing rapid response to air quality deterioration
5. Providing reliable data with which to validate air quality models and new monitoring methods
6. Providing timely information on air quality to all interested parties including the general public

Monitoring strategies can be summarised in terms of spatial representativity (i.e. siting criteria, including fixed or mobile and numbers of sites), time resolution and measurement accuracy. Network design will of course be constrained by the available technologies and cost. Currently the main focus for monitoring networks is to satisfy the requirements of air quality legislation, as described in the next section.

2 Current Legislative Monitoring Requirements in Different Parts of the World

2.1 USA

The US Environmental Protection Agency (EPA) is required to set up National Ambient Air Quality Standards for substances possibly harmful for humans or the environment. This requirement is formulated in the Clean Air Act, last amended in

Table 2 Air pollutants regulated by the National Ambient Air Quality Standards as of October 2011 [12]

Pollutant (final rule cite)	Primary/secondary	Avg. time	Level	Form
Carbon monoxide	Primary	8 h	9 ppm	Not more than one exceedance per year
		1 h	35 ppm	
Lead	Primary + secondary	3 month average	0.15 μg/m^3	Not to be exceeded
Nitrogen dioxide	Primary	1 h	100 ppb	8th percentile, averaged over 3 years
	Primary + secondary	Annual	53 ppb	Annual mean
Ozone	Primary + secondary	8 h	0.075 ppm	Annual 4th highest daily max. 8-h concentration, avg. over 3 years
Particles $PM_{2.5}$	Primary + secondary	Annual	15 μg/m^3	Annual mean, avg. over 3 years
		24 h	35 μg/m^3	98th percentile, avg. over 3 years
PM_{10}	Primary + secondary	24 h	150 μg/m^3	Max. one exceedance per year, over 3 years
Sulphur dioxide	Primary	1 h	75 ppb	99th percentile of 1-h daily max. concentrations, averaged over 3 years
	Secondary	3 h	0.5 ppm	Not to be exceeded more than once per year

1990, which also differentiates between primary standards providing public health protection, including protecting the health of "sensitive" populations such as asthmatics, children and the elderly, and secondary standards providing public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation and buildings. The criteria air pollutants, applicable throughout the USA, are listed with their limit values, called "Ambient Air Quality Standards" in the USA, in Table 2.

Two main networks are differentiated in the USA: the state and local air monitoring stations (SLAMS) and the national air monitoring stations (NAMS). The two networks mainly differ in their requirements with respect to area of coverage with more, smaller-scale representative monitoring sites within the SLAMS. The objectives, primarily for SLAMS, as laid out in CFR 40 [13] are to:

(a) Provide air pollution data to the general public in a timely manner
(b) Support compliance with ambient air quality standards and emissions strategy development
(c) Support air pollution research studies, specifically providing data for researchers working on health effects assessments and atmospheric processes, or for monitoring methods development

Both networks, SLAMS and NAMS, use the same siting criteria as laid out by the US EPA, differentiating micro, middle, neighbourhood, urban, regional and national to global scale [13]. This differentiation is solely based on their spatial

scale of representativeness. Representativeness can be seen as an area surrounding the measurement site where air pollutant concentrations are reasonably similar to those measured at the monitoring site.

Based on the objectives and scales of spatial representativeness needed, CFR 40 [13] differentiates six site types:

(a) Sites located to determine the highest concentrations expected to occur in the area covered by the network,
(b) Sites located to measure typical concentrations in areas of high population density,
(c) Sites located to determine the impact of significant sources or source categories on air quality,
(d) Sites located to determine general background concentration levels,
(e) Sites located to determine the extent of regional pollutant transport among populated areas; and in support of secondary standards and
(f) Sites located to measure air pollution impacts on visibility, vegetation damage or other welfare-based impacts.

Each site type matches a certain need of spatial representativeness. For example, sites located to determine local hot-spots are at places where the highest concentrations are expected and will mostly be microscale monitoring sites, while those measuring air pollution impacts on visibility and vegetation damage have to be representative over regional to national scale.

CFR 40 [13] reflects this not only in general form but also with respect to specific pollutants. Ozone, a typical large-scale secondary pollutant (formed in the gas phase in polluted air) accordingly has only to be measured at urban and larger scales during the "ozone season", as derived from seasonal measurements for each federal state and listed in CFR 40 [13]. In contrast, the main areas required to monitor for CO and NO_2 are at the micro- and middle-scale where the highest concentrations and exposure may occur. It is interesting to note that microscale (near road) NO_2 measurements according to CFR 40 [13] are required to be conducted "within 50 m of target road segments in order to measure expected peak concentrations". A microscale site typically represents an area impacted by the plume with dimensions extending up to approximately 100 m. The distance from a source is a very critical parameter when compliance to limit values is required.

The current strategy and approach for air quality monitoring networks in the USA is therefore best described as pursuing the aims of ensuring the achievement of air quality limit values, air quality control, and allowing rapid intervention to prevent air quality deterioration.

2.2 Asia

Air quality standards and monitoring strategies across Asia are diverse and exhibit many differences between the countries. For brevity only the standards and monitoring concept for Japan are presented in any detail. For Taiwan, India, China and

Table 3 Japanese air quality standards (based on [15])

Pollutant		Avg. time	Level	Form
Carbon monoxide		24 h	10 ppm	Not to be exceeded
		1 h	20 ppm	For any consecutive 8 h period
Lead				No limit value
Nitrogen dioxide		24 h	0.04–0.06 ppm	Values to be within or below that zone
Ozone[a]		1 h	0.06 ppm	Not to be exceeded
Particle pollution	$PM_{2.5}$	Year	15 μg/m^3	Not to be exceeded
		24 h	35 μg/m^3	Annual 98th percentile value
	PM_{10}			The daily average for hourly values shall not exceed 0.10 mg/m^3, and hourly values shall not exceed 0.20 mg/m^3
Sulphur dioxide		24 h	0.04 ppm	Not to be exceeded
		1 h	0.1 ppm	Not to be exceeded

[a]Defined as oxidising substances (e.g. O_3 and PAN, peroxyacetyl nitrate) capable of isolating iodine from neutral potassium iodide, excluding nitrogen dioxide

other Asian countries, please refer to the corresponding webpages [14]. The Japanese air quality standards are summarised in Table 3.

The Japanese "Air Pollution Control Law" dates back to 1968 and was designed to promote comprehensive air pollution control measures. Subsequent revisions have included extensions of regulatory objects, nationwide regulation and enforced standards, e.g. those for specific dust (asbestos) in 1989, vehicle fuel in 1995, harmful air pollutants in 1996 and volatile organic compounds (VOC) in 2004.

Article 1 of the recent Japanese Air Pollution Control Law [16] states:

> The purposes of this Law are as follows.
>
> One is to protect the *public health* and *preserve the living environment* with respect to air pollution, by controlling emissions of soot, smoke and particulate from the business activities of factories and business establishments; by controlling emissions of particulate while buildings are being demolished; by promoting various measures concerning hazardous air pollutants; and, by setting maximum permissible limits for automobile exhaust gases, etc.
>
> The other is to help victims of air pollution-related health damage by providing a *liability regime* health damage caused by air pollution from business activities.

It is interesting to note that this law clearly indicates a liability regime for those who were harmed which is not the case in the corresponding laws of the USA and the European Union.

2.3 Europe

Air Quality is regulated at the European Union level by Directive 2008/50/EC [17] with currently one additional directive (2004/107/EC) [18] covering arsenic, Cd, Hg, Ni and polycyclic hydrocarbons (PAH) in air. The European directives

include more pollutants than those listed by the US EPA as "criteria air pollutants common throughout the United States"; specifically As, Ni, PAH, specifically benzo(a)pyrene), Hg and Cd.

The Directive requires air quality monitoring for the protection of human health and the environment. This is specifically addressed in the Directive preamble which states that air pollution has to be reduced to such a level that any harm to humans is kept at a minimum and takes special account of the needs of sensitive subpopulations, such as children and elderly people.

Monitoring of additional, non-regulated substances is also requested at regional background locations (EMEP sites) to (a) compare rural concentrations to those in other areas, e.g. urban concentrations, (b) identify and quantify regional sources and their contributions and (c) allow the assessment of the trans-national movement of air pollutants. Substances requested for this type of regional background station are the anions and cations SO_4^{2-}, NO_3^-, Mg^{2+}, Ca^{2+}, NH^{4+}, Cl^-, Na^+, K^+, plus elemental carbon and organic carbon, in the $PM_{2.5}$ particle size fraction.

Table 4 summarises the air quality standards stipulated in the 2008 EC Directive. Additionally, benzene is regulated not to exceed 5 μg/m^3 as an annual average.

The European Directive [17], like the US regulations, differentiates separate site types for the protection of human health and the environment. Three main site types are defined for health purposes:

- Hot-spot monitoring: Publicly accessible areas in urban environments where highest concentrations of a pollutant are to be expected, including areas influenced by traffic or industrial emissions,
- Urban area monitoring: Measurements conducted at a location representative of a larger area to represent population exposure,
- Rural area monitoring: A sampling location which is not influenced by industry or city areas within the surrounding 5 km.

A single site type is defined for the protection of the environment; these are regional background sites designed to represent an area of at least 1,000 km^2. Regional background monitoring sites should be at least 5 km from significant sources and more than 20 km away from any conurbation.

In addition to the above site criteria, microscale requirements are set out within the European directive [17]. Traffic-related hot-spot sampling locations shall not be more than 10 m away from the edge of the traffic lane and should be representative of a road length of 100 m. The Directive [17] additionally gives further recommendations including distances from walls and sampling height.

2.4 Comparison of the Air Quality Monitoring Strategies

A comparison of the air quality strategies of the USA, Japan and Europe reveals many similarities.

Table 4 Air pollutants regulated in Europe (based on [17])

Pollutant		Avg. time	Level	Form
Carbon monoxide		8 h	10 mg/m^3	Not to be exceeded
Lead		Annual	0.5 μg/m^3	Not to be exceeded
Nitrogen dioxide		Annual	40 μg/m^3	Not to be exceeded
		1 h	200 μg/m^3	Not to be exceeded more than 18 times a year
		Annual	30 μg/m^3	As NO_x, for environmental protection: Not to be exceeded at regional sites
Ozone		8 h	120 μg/m^3	For health protection: Not to be exceeded more than 25 times per year, averaged over 3 years
		AOT40	18,000 μg/m^3*h	For environmental protection: Sum of differences between 8 am and 8 pm of hourly value exceeding 80 μg/m^3 between May and July over 3 years
Particles	$PM_{2.5}$	Annual	25 μg/m^3	To be reached in steps with no exceedance in 2015
		AEI[a]	20 μg/m^3	Not to be exceeded
	PM_{10}	Annual	40 μg/m^3	Not to be exceeded
		24 h	50 μg/m^3	Not to be exceeded more than 35 times a year
Sulphur dioxide		24 h	125 μg/m^3	Not to be exceeded more than 3 times a year.
		1 h	350 μg/m^3	Not to be exceeded more than 24 times a year
		Annual	20 μg/m^3	For environmental protection: Not to be exceeded at regional sites

[a]Average Exposure Indicator: the representative mean of urban background monitoring stations in a country, calculated as a rolling 3-year average

All strategies

- Contain elements of emission monitoring (not further discussed in detail)
- Assume a link between emissions and ambient air quality
- Define site types depending on distance to major sources of air pollution
- Rely on a combination of emission control and ambient air quality monitoring
- Include limit values for the safety of the population and the environment
- Stress the importance of providing timely information to the public

Strong similarities can also be seen between the lists of regulated air pollutants in Tables 2, 3 and 4. There are some air pollutants beyond those listed in the tables that are also required to be monitored, including volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs).

Still significant differences exist in

- The area of liability

European law does not state anything concerning liability in the case of harm or damage by air pollution, whereas specific sections are dedicated to this question in Japanese law.

- Definition of site types

While the general idea of differentiating monitoring site types is present in all the monitoring strategies, the site type definitions and descriptions are different. The USA approach starts with different scales of representativity which are then linked to

specific monitoring aims. The European Directive [17] approaches site definitions from the other direction, by defining the monitoring aim and describing the site types needed; distances to sources are stipulated and specific siting criteria have to be fulfilled. It is also important to note that sampling and siting is more stringently defined in the European Directive compared with the USA requirements.

- Microscale siting requirements and pollutants

Even though the major air pollutants and limit values appear very similar, significant differences may arise from different siting requirements. CFR 40 [13] states that near road measurements, which are only required for NO_2 and CO, are to be conducted within 50 m of the target road segment. No near-road measurements are required for, e.g. particulate matter $PM_{2.5}$ and PM_{10} in the USA. By contrast, the European Directive [17] requires near-road measurements in a maximum distance of 10 m from the road edge for a larger variety of pollutants (SO_2, NO, NO_2, PM_{10}, $PM_{2.5}$, lead, benzene and CO). Various studies have shown the rapid decrease in primary pollutant concentrations with distance from roads; concentrations can be 20–40% lower for $PM_{2.5}$, PM_{10} and particle number (both $<$100 nm and 0.5–20 μm in diameter) at 50 m away from a road compared with concentrations at 10 m [19, 20]. This means that the US limit value of 100 ppb for NO_2 is not equivalent to its European counterpart, even though 100 ppb $\approx$ 200 μg/m^3. It is actually about 40% higher (140 ppb) if concentrations in comparable locations are considered.

- The concept of population exposure

The European Directive [17] is alone in having the concept of regulating population exposure via an average exposure indicator (the AEI for $PM_{2.5}$). This means that an average urban background concentration for a country is calculated and regulated. The concentrations determined at this site type are considered to be the most exposure-relevant for the population. This approach is based on cost–benefit analyses comparing the benefits of focussing on hot spots (in response to a limit value approach) with those from efforts affecting larger areas [21]. Given the absence of evidence for a threshold for PM health effects, it is more beneficial for the general health of the population, and more cost effective, to decrease the average pollution exposure for the whole population than it is to decrease the concentration at highlighted locations in a populated area. The “hot-spot approach” with attainment of limit values at all relevant measurement sites is still pursued, as in the other countries, in parallel.

3 How Do Air Quality Monitoring Technologies Influence Strategies?

Robust air quality monitoring is based on the quantification of pollutant concentrations with a high degree of accuracy, precision, comparability and long-term stability. Accuracy and precision of measurements are essential for the assessment of limit value attainment and law enforcement to improve ambient air quality.

Early techniques used in regular monitoring were bulky and often relied on air sampling with subsequent laboratory analysis. Volz and Kley [22] describe early methods to measure O_3, initially employed in 1876. Here a defined volume of air was bubbled through a solution of AsO_3^{3-} which reacted with O_3 to form AsO_4^{3-}. The amount of AsO_3^{3-} was then titrated with I_2 to determine the O_3 concentration. Other early air quality monitoring techniques focused on the measurement of airborne particles. The use of fibrous filters for sampling airborne particles was invented around 1920 (see [23]) and became standard for ambient air quality monitoring after 1940. The method of manually weighing a filter prior to and after sampling a defined volume of air is still in use, and it is currently the basis of reference methods for the determination of PM_{10} and $PM_{2.5}$ in the EU and US.

Measurements using sampling techniques and subsequent laboratory analysis are labour intensive, costly and do not meet the need for timely dissemination of air pollution information to the public.

Developments in the 1970s and 1980s allowed the first measurements of gases to be made using automated measurement techniques. Good examples include the techniques developed for the measurement of oxides of nitrogen, O_3, CO_2, particle mass and soot (black carbon).

The oxides of nitrogen (NO and NO_2) can be determined with a method based on chemiluminescence, compound-specific light emission after excitation. The principle of this method is based on the following chemical reaction:

$$NO + O_3 \rightarrow NO_2 * + O_2 \tag{1}$$

$$NO_2 * \rightarrow NO_2 + hv \tag{2}$$

The addition of O_3 and measurement of the light intensity at the specific wavelength (2) in a reaction chamber can be used for continuous NO measurements [24] and for NO_2 if this is catalytically reduced to NO as part of the process.

Light absorption at specific wavelengths is another principle often employed for the online measurement of gaseous pollutants. For example, the absorption of O_3 in the ultraviolet at 254 nm can be used, though this experiences cross sensitivity to SO_2 and PAHs, and CO_2 in the infrared at 4.26 μm (2,350 cm^{-1}), which has little cross sensitivity to other gases. The most common C–H absorption bands are in the range of 3.33–3.57 μm (2,800–3,000 cm^{-1}).

While these methods can readily be employed in "real time", light absorption of soot particles was first developed for laboratory measurements of particles collected on filters and then adapted for online deployment [25]. Sampling on filter tapes allows quasi-continuous measurement by recording the decrease of transmitted light and moving the tape when the exposed area becomes too dark.

Parallel developments in health research, especially empirical studies, have gone hand in hand with new air pollution measurement technologies and have led to a substantial body of evidence on the adverse effects of air pollution. Put simply, new

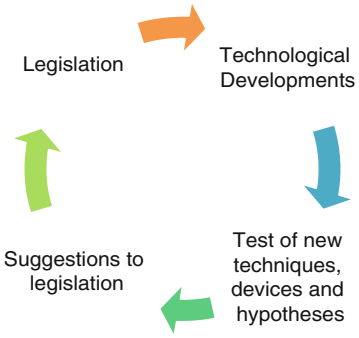

Fig. 1 Interlinkage between new measurement techniques and findings with the development of legislation

measurement technologies and new hypotheses in the environmental health arena have triggered research and taken forward our understanding of air pollution and health, which has in turn fed into legislation and emission controls.

Automated, quasi-online systems with highly time-resolved measurements, and the improvement of data storage and telecommunication technologies, have led to the current standardised system of air quality monitoring. This is based on fixed monitoring sites at different locations representing different site types. The sites are equipped with standardised monitoring devices for the regulated air pollutants and other optional measurements. The standardisation of the measurement methods is undertaken by the standardising and regulation bodies of the corresponding countries or legal jurisdictions, e.g. the US EPA for the USA, the VDI/DIN (Verein deutscher Ingenieure/deutsche Industrienorm) for Germany, CEN (Comité Européen de Normalisation) for the European Union, JIS (Japanese Industrial Standards) for Japan, and by ISO (International Standard Organisation) for worldwide harmonisation of air quality measurements.

Online data exchange is now possible with the standardised automated measurement methods being employed combined with telecommunication links. This data exchange allows for timely public air quality data to be sent via video text, the Internet, telephone and smartphones, as requested in the legislation.

The historical development of air quality measurements over the last 100 years has clearly influenced the monitoring strategies. These changes have not come spontaneously, but in a cycle, or rather in a spiral of related developments (Fig. 1).

Hence air quality monitoring today is a vibrantly developing area, employing new technologies and improving the understanding of human and environmental health effects, to work towards quality-of-life improvements for the population.

4 Recent Technological Developments

Emerging measurement technologies look to enable new monitoring paradigms. An analysis of available and recent developments in air quality monitoring technologies within the European Project "AirMonTech[1]" identified several major areas of development:

(a) Multi-component analysis,

Most current automated measurement techniques focus on one or possibly two air pollutants. A survey of recent developments shows major advances in multi-component analysis. Examples include:

Online liquid chromatography systems (e.g. Marga) which sample airborne particles into a liquid which is subsequently analysed in the field for (soluble) particle components such as SO_4^{2-}, NO_3^-, Cl^-, Ca^{2+}, Mg^{2+}, K^+ and Na^+ [26].

The development of aerosol mass spectrometers (AMS), starting with work by Allen and Gould [27] and Sinha et al. [28], which focusses mainly on compounds ionisable at temperatures below 1,300°C such as sulphates and organic matter. Recently Park et al. [29] have developed a laser-induced ionisation method also allowing the detection of some metals and metal oxides. AMS without particle size separation are now small enough in size and power consumption to be used in long-term monitoring networks [30].

Multi-elemental analysis by non-destructive X-ray fluorescence (XRF) is possible on filter tape samples similar to those collected for particle light absorption measurements. Up to 23 elements with the atomic number of potassium and above can be analysed by this method simultaneously, with a time resolution down to 15 min.

(b) Small, low cost, portable devices with low power consumption,

Existing technologies are being miniaturised and new small devices are being developed. Good examples are handheld condensation particle counters (CPCs) (e.g. TSI 3007) measuring submicrometer particle number concentrations, hand-held and portable devices for submicrometer particle surface area concentrations (sometimes along with particle number concentrations) as summarised and compared in Asbach et al. [31], and small personal black carbon (particle light absorption) monitors (e.g. the microAeth™). The development of sensors based on micro-electro-mechanical systems (MEMS) for PM mass concentrations, and electrochemical and semiconductor systems for gases, which are small enough to be implemented in smartphones also offers new and interesting possibilities (e.g. [32]).

An emerging trend towards combining different sensors and measurement technologies for urban air quality monitoring along with device miniaturisation is evident from new commercially available equipment such as ETL 200 by Casella (Italy), simultaneously measuring NO, NO_2, CO, O_3, benzene and noise, or the

[1] www.AirMonTech.eu

airpointer™, simultaneously measuring four compounds using EU reference methods (MLU, Austria).

These small, flexible devices open up two new monitoring paradigms: (1) personal exposure and mobile monitoring and (2) measurements at a multitude of fixed sites which can also be flexibly located in living areas where current monitoring "containers" cannot be placed.

(c) Alternative parameters for particulate air pollution,

The link between exposure to air pollutants and adverse health effects is well established, but the causal biological mechanisms are not clear and this is especially the case for particulate matter health effects. Airborne particulate matter is extremely variable in chemical composition, size and morphology; all parameters of possible health relevance. This and the different health endpoints affected by exposure to ambient PM make the situation very complex. It may well be that more than one particle characteristic is needed to effectively describe the harmful outcomes of exposure. Possible parameters under discussion are particle number concentration, which is dominated by particles below 100 nm in size; the so-called ultrafines [33], particle surface area concentration, which is dominated by particles around 200–800 nm in diameter [34, 35], black carbon or black smoke [36], or the reactivity of particles with respect to redox reactions, or their potential to form radical oxidative species (ROS) [37]. These and some other alternative particulate indicators are currently discussed [38] and investigated in several large European and US studies such as ESCAPE and Transphorm[2].

(d) New methods for data retrieval and analysis.

Next to the development of new measurement technologies, the most important developments are in data retrieval and statistical data analysis. Air pollution data are now regularly remotely retrieved, automatically stored in a database, checked for consistency and made publicly available via the Internet, for example.

Resch et al. [39] summarise and discuss the whole chain from data retrieval, processing, analysis and visualisation. The general design and structure of such a chain is depicted in Fig. 2, starting with generalised sensors. These sensors can be traditional fixed monitors, but can also be mobile sensors installed on cars, ships or at short-term locations, for example on lampposts. These mobile or moveable sensors can be equipped with a geo-positioning system (GPS) to be employed in geo-information systems (GIS) (e.g. [40]). These applications have been made possible by miniaturisation of the GPS as well as the transfer of data by mobile phone systems.

Gross [41] very nicely described the development of such a GIS-based information system:

> In the next century, planet earth will don an electronic skin. It will use the Internet as a scaffold to support and transmit its sensations. This skin is already being stitched together.

[2] www.escape.eu, www.transphorm.eu

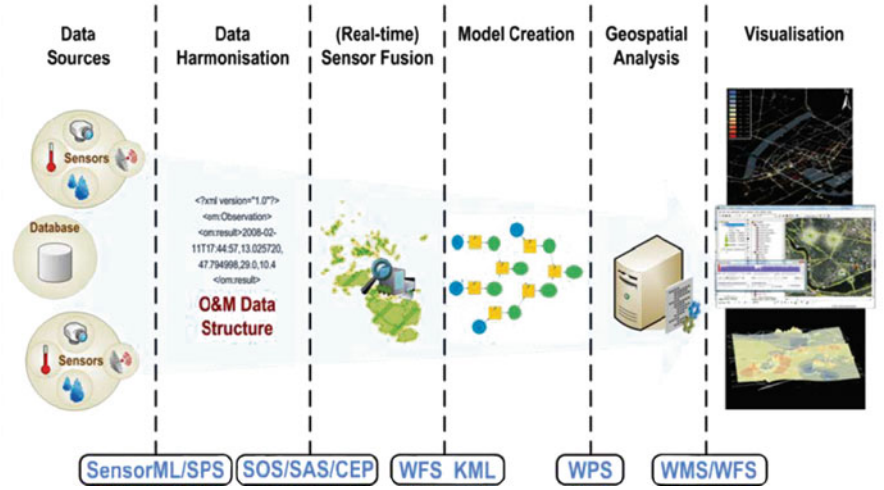

Fig. 2 Flow of data and analyses in modern GIS-based sensor networks (from [39])

> It consists of millions of embedded electronic measuring devices: thermostats, pressure gauges, pollution detectors, cameras, microphones, glucose sensors, EKGs, electroencephalographs. These will probe and monitor cities and endangered species, the atmosphere, our ships, highways and fleets of trucks, our conversations, our bodies – even our dreams. (citation from [41])

This envisages the collection of all different types of information, including air quality. The next and very important step towards making such an effort worthwhile is the harmonisation of the collected data, for subsequent modelling, as well as geospatial and logical data analysis. At this point visualisation and heterogeneous data interpretation along with the conditional triggering of actions become possible. This latter analysis is dependent on a very good understanding of the measurement devices, the data and the logical environmental processes, together with an evaluation mechanism or standard for the integrated data.

In summary, significant advances have been made during the last decade and recent and foreseeable developments in air quality monitoring technologies now allow new air quality monitoring concepts to be created and explored.

5 Possible Future Monitoring Strategies

Current monitoring strategies are mainly aimed at fulfilling legal obligations and assessing limit value compliance. These strategies, however, are built around the assessment of background concentrations as a surrogate for population exposure. Future monitoring strategies may harness new technologies to bring the measurements as close

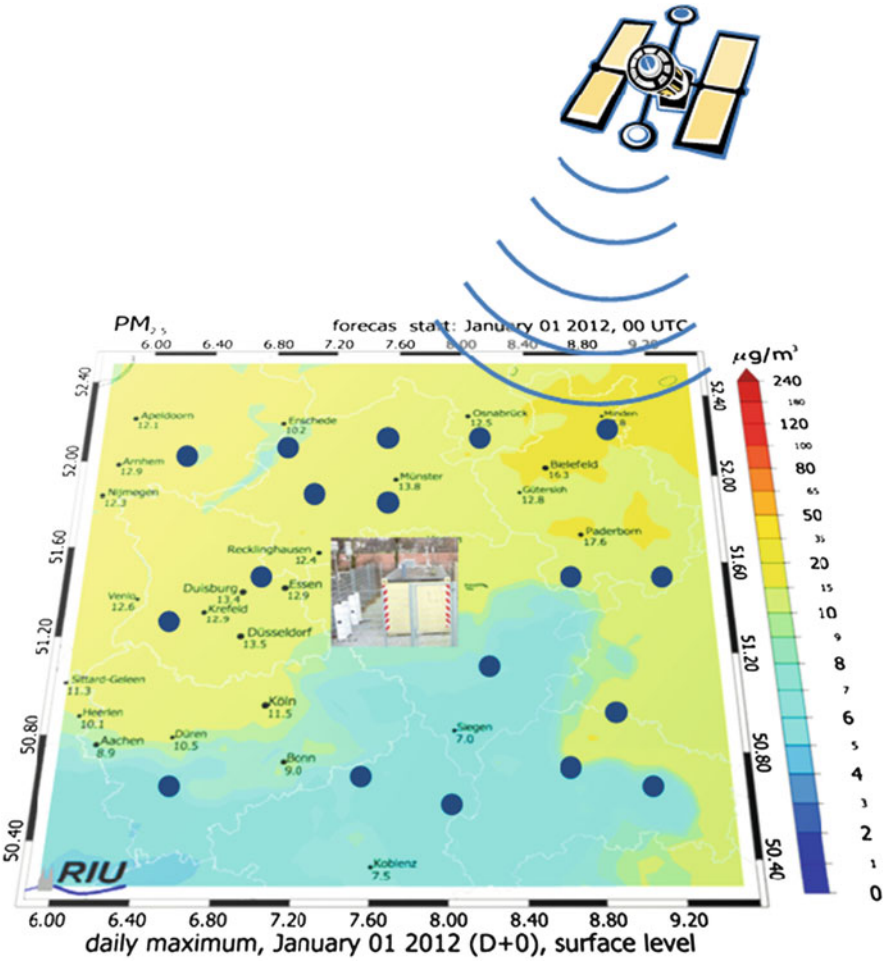

Fig. 3 Visualisation of a future monitoring concept linking all available monitoring tools, fixed site measurements, mobile and flexible measurements, modelling and satellite observations

to exposure assessments as possible. This cannot be pursued based solely on the use of fixed monitoring sites.

A possible future concept is depicted in Fig. 3. This shows the four basic possibilities for ambient air quality monitoring:

- High quality and high time-resolution measurements of air pollutants at fixed locations,
- Mobile and flexibly installable monitoring devices with low power consumption which might still need a protective container, delivering data of relatively high quality, or alternatively could be low cost sensors used very flexibly, e.g. at lampposts or on buses,

– Modelling of the spatial and temporal variation of air pollutants in urban areas, using improved emissions inventories and
– Satellite observations of air pollutants and meteorology to derive information on parameters influencing urban air quality.

Each of the four possibilities has shortcomings with the most significant ones being the

– Limitation of the spatial representativity for fixed monitoring sites,
– Significantly lower precision, comparability and time resolution for the small mobile or flexibly installable devices,
– Relatively high uncertainty of models, which need verification and validation inputs from monitoring data and
– Poor vertical resolution, in the case of satellite measurements, to be of relevance for ground-level human and environmental exposure.

The advantages and limitations of the different monitoring possibilities illustrate the significant challenges that need to be addressed to allow new air quality monitoring tools to be combined to maximum advantage.

Taking the example in Fig. 3, we can envisage that the fixed monitoring sites with high quality measurements act as reference sites for the collocation and on-going comparison with small, flexible monitoring devices. This "online" reference comparison would allow for dynamic correction and hence decreased measurement uncertainty for the dispersed monitors in an urban area. The combined spatially and temporally resolved data from the fixed and flexible monitors could then be used to validate the model results, along with satellite observations, meteorological data and emissions information, which generally need some improvement [42] (Fig. 4).

The functions of future urban air quality networks will not change dramatically but new facilities will be enabled, new developments can be tested and monitoring can be extended to routinely link air quality to its effects.

The current focus of air quality monitoring on limit value compliance and the calculation of population exposure can be continued on the basis of the fixed monitoring sites. As new technologies are installed and utilised, the use of modelled data based on fewer fixed monitoring sites, networks of mobile, flexible monitors and atmospheric models can be explored. Validated model results may be seen as being more reliable to derive a long-term population exposure value than those based on fixed monitoring sites. This approach allows linkages between the higher data quality obtained by measurements with spatial information obtained from model results to be developed.

The new network design will allow and facilitate new developments through

– New monitoring devices, either for the fixed or the mobile, flexible measurement locations,
– Testing new data collection, analysis and visualisation tools,
– Improved exposure assessments for cohort as well as population-based health effect studies,

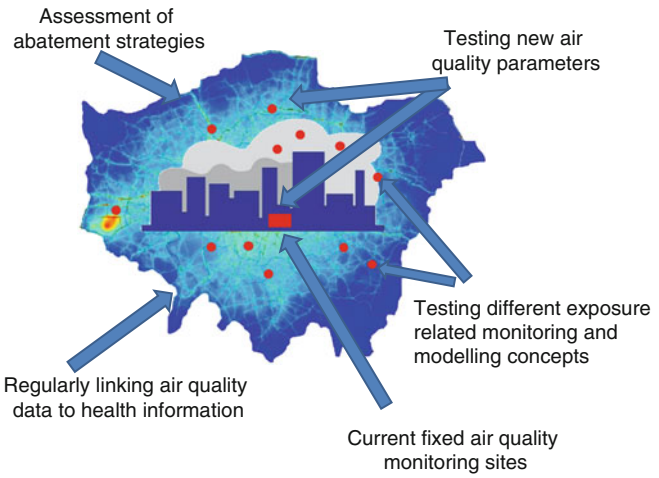

Fig. 4 Conceptual purposes and tasks of the future urban air quality networks

- Routine linkages between public health data and environmental stressors, specifically urban air quality, assess the effectiveness of abatement strategies,
- The assessment of new or alternative air quality parameters to test their use in the context of urban air quality and health.

It is important that we enable and facilitate such developments in Europe to continue the improvement of its air quality. The new directions will improve our understanding of air quality in urban environments, allowing us to bring forward the best and most cost-effective abatement measures for minimising the significant impacts of urban air pollution.

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