PRIORITIZING INNOVATIONS IN MONITORING

Vital Strategies

Bloomberg Philanthropies

Accelerating City Progress on Clean Air

Innovations in Monitoring to Strengthen Air Quality Management in Indian Cities

To access the full report, visit www.vitalstrategies.org/cleanairguide

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These materials are an extract and adaptation of the more comprehensive Innovation and Action Guide, which includes sections on ambient air qualtiy monitoring, assessing emissions and sources, data availability, access, and use, and organization for action.

To access the full report visit www.vitalstrategies.org/cleanairguide

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Co-authors and main contributors
Joshua Apte, University of Texas, USA; Michael Brauer, University of British Columbia, Canada; Sarath Guttikunda, UrbanEmissions.info, India; Carisse Hamlet, Vital Strategies, USA; Christa Hasenkopf, OpenAQ, USA; Daniel Kass, Vital Strategies, USA; Thomas Matte, Vital Strategies, USA; Sumi Mehta, Vital Strategies, USA; Vivian C. Pun, Vital Strategies, Singapore; Solomon Teffera, SolTeff Environmental Consulting, USA; Christine Wiedinmyer, University of Colorado Boulder, USA

External reviewers
Lu Fu, Clean Air Asia; Iyad Kheirbek, C40; Michal Krzyzanowski, University College London; Driejana Ir Radan, Institute of Technology Bandung; Pallavi Pant, Health Effects Institute; Jon Samet, University of Colorado; Sara Terry, US Environmental Protection Agency; Supat Wangwongwatana, Asia Institute of Technology; Simon Ng, Business Environment Council; Bidya Banmali Pradhan, International Centre for Integrated Mountain Development; Premakumara Jagath Dickella Gamaralalage, Institute for Global Environmental Strategies.

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Executive Summary

Innovative Solutions for a Deadly Problem

Air pollution continues to be the deadliest global environmental health risk, causing nearly 5 million deaths each year, mainly from exposure to fine particles ($PM_{2.5}$). The burden of air pollution is greatest and increasing in countries with rapid economic development and urbanization, along with a proliferation of emissions from industry, electric power generation, and motorized transport. In countries with limited or no air quality regulation, this causes steep increases in harmful pollution. Compounding the air pollution challenge in many of these countries is the persistence of pre-industrial pollution sources such as burning of household solid fuels, crop waste and forests for land clearing as well as open trash burning. The global air pollution crisis is closely linked to rapidly worsening impacts of climate change that will continue to grow without rapid and aggressive action to reduce climate forcing pollutant emissions.

For many city governments in many low- and middle-income countries, the complexity and cost of understanding and controlling air pollution have been barriers to initiating or sustaining effective clean air action. Limited national policies on air pollution also create a void of guidance. A new approach in air quality management that combines conventional solutions with innovations in monitoring, assessment, data use, and organization can accelerate clean air action, especially in cities with presently limited technical capacity. Decades of progress in high income countries have shown that government action can reduce air pollution even as economies and populations grow. In combination with innovative solutions, the investments and strategies developed in wealthy countries to scale up efficiency, cleaner fuels, and emission control technology for vehicles, electricity generation, buildings, and industry can now be leveraged cost-effectively for deployment in low- and middle-income countries.

The full report—*Accelerating City Progress on Clean Air: Innovation and Action Guide*—provides a comprehensive framework for understanding and deploying innovation and partnership models that inform, evaluate, and build sustained support for local, regional, and national clean air measures.

This guide, produced by Vital Strategies staff and other experts on air quality management, is mainly intended for government officials, technical partners and other stakeholders in cities and metropolitan areas with limited local air quality management capacity and with levels of air pollutants that are well in excess of health-based standards and/or increasing steadily. It is also relevant to similar audiences at state/provincial and national levels seeking to accelerate clean air actions. It describes how to build on past successes and deploy recent innovations and partnership models to reduce the complexity and cost of obtaining and using data to inform, implement, evaluate and build support for sustained clean air actions.

A New Approach to Air Quality Management

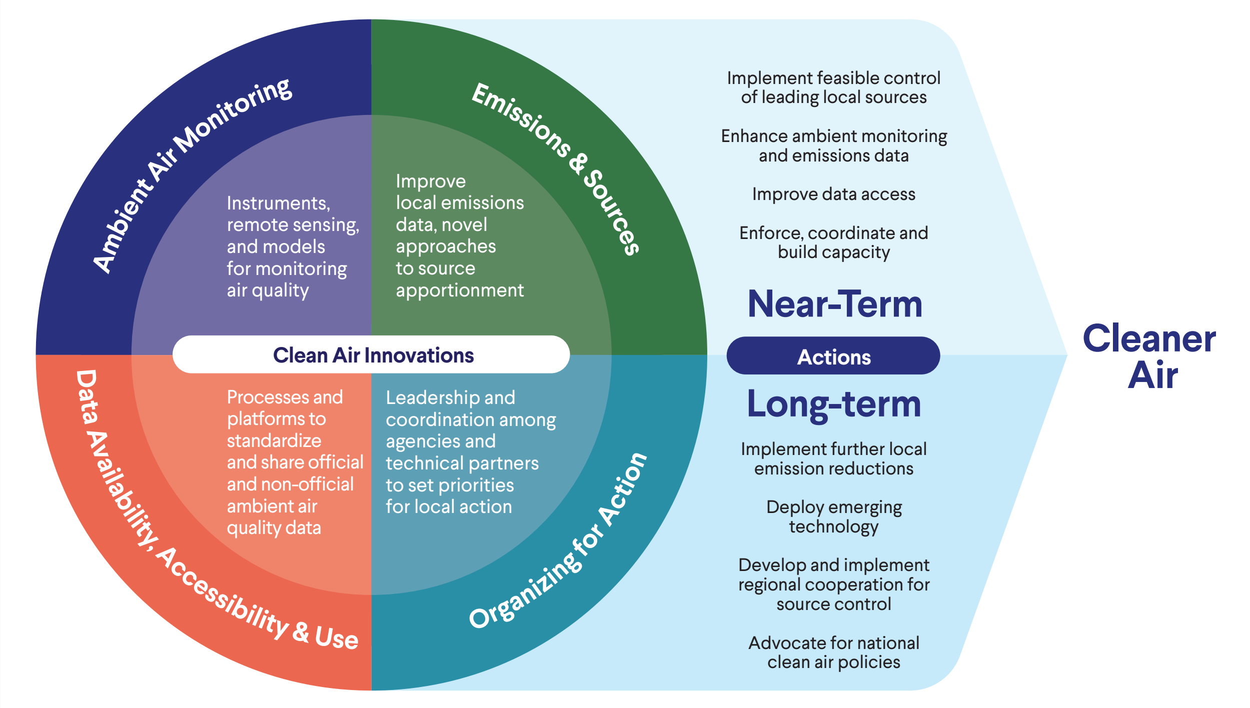
The guide lays out a new approach to accelerate clean air progress in cities within low- and middle-income countries. It recognizes air pollution as a massive public health crisis with unique, but solvable challenges faced by urban areas in low- and middle-income countries with limited air quality management capacity.

Each of the four main sections of the guide (ambient air quality monitoring; assessing emissions and sources; data availability, accessibility, and use; and organization for action) aims to answer questions about each component's key role in urban air quality management and to lay out a pragmatic, phased approach to launching and building clean air activities, with methods and activities suited to local capacity.

- In the three technical sections, local capacity is classified into four phases:
  1. Limited or none
  2. Basic—sufficient to support initial actions
  3. Comprehensive—able to support sustained actions
  4. Advanced—exceeding capacity of many cities in high-income countries

- The guide provides visual keys to indicate content that is most relevant to a city based on its current capacity to manage air quality, as well as its plans to augment them in the near term.

Innovations to promote clean air action: Overall framework



- City case studies provide applied examples of how cities around the world at various stages of air quality technical capacity and political commitment took actions to control important sources or develop actionable data.

Ambient Air Quality Monitoring

This extract reviews the strengths and limitations of both conventional and innovative monitoring approaches—including satellite remote sensing, advance surface monitoring, and hyperlocal monitoring—while aligning each approach with its appropriate monitoring capacity phases.

Objectives by local capacity phase:
Phase 1: Establish the need and plan for official monitoring, especially for $PM_{2.5}$
Phase 2: Establish and maintain official $PM_{2.5}$ monitoring, and plan for monitoring enhancements
Phase 3: Monitor $PM_{2.5}$ composition and additional pollutants, increase monitor coverage
Phase 4: Enhance spatial resolution within the urban area with an advanced, integrated system

Innovations in monitoring technology, remote sensing and modeling can provide actionable air pollution data more rapidly and at lower cost than conventional regulatory monitoring approaches. However, the explosion in new monitoring approaches, products and data also has the potential to increase complexity and costs, create confusion among the general public, and make it more difficult for governments and citizens to build a shared understanding of a city's air pollution problem and how to address it. A stepwise approach to prioritizing innovations to strengthening air quality monitoring can help reduce complexity and avoid monitoring pitfalls, combining conventional regulatory monitoring approaches with innovations. A combination of monitoring approaches can inform a robust air quality management program, support the needs of local, regional, and national air quality management, and provide data for research and public information.

Accelerating urban clean air progress in Indian cities

Audience for this guide

This guide is mainly intended for government officials, technical partners and other stakeholders in cities and metropolitan areas with limited local air quality management capacity and with levels of air pollutants that are well in excess of health-based standards and/or increasing steadily. It is also relevant to similar audiences at state/provincial and national levels seeking to accelerate clean air actions. It describes how to build on past successes and deploy recent innovations and partnership models to reduce the complexity and cost of obtaining and using data to inform, implement, evaluate and build support for sustained clean air actions.

Overview

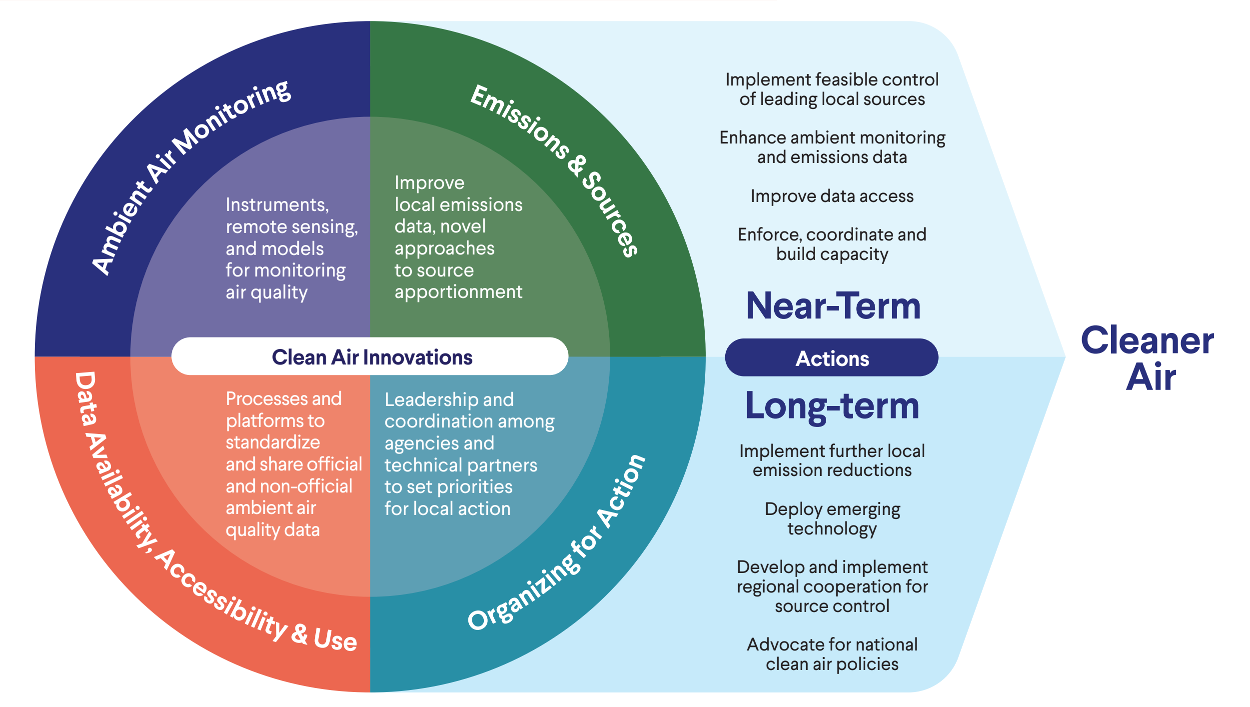
The full guide covers four aspects of clean air action: air quality monitoring; assessing emissions and sources; data accessibility and use; and government organization for action, and aims to answer practical questions about each topic (Figure 1f).

Innovations in air pollution monitoring, including low-cost sensors, have received a good deal of attention, but monitoring is only one aspect of air quality management. This guide also considers how available data and innovations in assessing air pollution emissions and sources can be used to inform clean air action plans, even in the absence of robust monitoring networks. The guide also addresses the importance of data availability, accessibility and use to inform and evaluate control measures and build public support for clean air actions. Finally, the guide addresses the need for commitment at executive levels of government and leadership to organize and coordinate multiple agencies, partners and stakeholders and build capacity for action.

Each of the technical chapters, 2-4, lays out a pragmatic, phased approach to launching and building clean air activities and describes approaches and activities suited to local capacity. This local capacity is classified into four phases: 1) Limited or none; 2) Basic, sufficient to support initial actions; 3) Comprehensive, able to support sustained actions; and 4) Advanced, exceeding capacity of many cities in high-income countries. Within a city, capacity may be more developed in some areas than others.

Figure 1f

Innovations to Promote Clean Air Action: Overall Framework



Depicted are four innovation domains considered in this guide: Ambient air monitoring (chapter 2); emissions and source assessment (chapter 3); data availability, accessibility and use (chapter 4); and organizing for action (chapter 5). Using innovations and conventional approaches across these domains, governments and partners in cities and other urban jurisdictions can obtain and apply actionable data, begin control of major local pollution sources in the near term, while improving monitoring and source data, building capacity, advancing additional local, regional and national clean air policies for sustained air quality improvements.

Overview of this guide

Each technical chapter

- Provides a brief overview of the topic;
- Describes phases that classify current capacity;
- Summarizes basic concepts about the topic; and
- Proposes implementation objectives and approaches suitable to each capacity phase.

Where appropriate, more detail on an approach is provided in the chapter and annexes. Several case studies describing actions taken at city and urban regional levels are included in this guide. Relevant case studies are referenced within the guide.

This guide not intended to replace available comprehensive air quality management guidance, e.g. (35). Rather it focuses on:

- How to combine recent innovations with conventional AQM approaches
- How to act in phases starting with steps suitable for highly polluted cities with limited AQM capacity
- Using data to inform near-term, local clean air action while planning and building capacity for sustained progress
- Distinguishing two roles for cities: taking local action and engaging advocacy and cooperation for regional and national actions
- Use of partnerships to augment and build government AQM capacity

Non-technical readers of this guide may find it helpful to reference Table 1g, “Essential Facts About Urban Air

Table 1g

Essential facts about urban air pollution

Despite the complexity of urban air pollution, a basic understanding of the health impacts, causes and solutions needed can inform effective use of clean air innovations and avoid pitfalls.

Ambient Air Monitoring	**Air pollution harms more than the lungs.** In addition to worsening asthma and COPD, air pollution causes heart disease, stroke, hypertension and cancers of the lung, larynx and nose and low birth weight. **Chronic exposure to low levels of pollution harm health.** Studies show larger cumulative health effects from long-term exposures than those from short-term exposures. The longer one is exposed to air pollution, the greater the risk of serious health harm; sustained improvements in air quality lead to improved population health and life expectancy. **A few well-placed monitors can identify unhealthy urban air quality.** $PM_{2.5}$ levels far above health-based standards at one or a few well-placed, high quality monitors or from satellite-based measurements demonstrate unhealthy air and the need to reduce emissions. More monitors can help identify hot-spots within a city. Ambient $PM_{2.5}$ levels tend to rise and fall across an urban area with changes in weather and increased proximity to sources. **Clear air does not always mean clean air.** While air pollution at very high concentrations can form visible haze and smog, air pollution concentrations high enough to harm health can be present when the sky is blue. Nine out of ten people worldwide live in places where air quality exceeds World Health Organization (WHO) health-based guideline limits.

Emissions and Sources	**Inefficient combustion from many small sources can add up to a major share of urban pollution.** These include household solid fuels for cooking and heating, diesel generator sets and open burning of trash, agricultural waste and to clear land. Motor vehicles – especially those powered by diesel, using high-sulfur fuel or lacking modern emission controls – can be important sources, as can industrial facilities, like brick kilns, steel mills and electric power facilities – especially those burning coal. **Household and outdoor pollution are related.** Emissions from solid fuels used by households for cooking, heating or hot water are a major source of both indoor and outdoor pollution in many regions. Fine particles in the outdoor air also penetrate the indoor environment, mixing with pollution from indoor sources, such as household cooking and environmental tobacco smoke. Local and regional sources are both important. Air pollution in cities comes from both local sources and from regional and upwind emissions – sometimes from hundreds of miles away.
Organization for Action	**Clean air actions are needed within and beyond cities.** Cities must reduce emissions within their jurisdiction while working to advance clean air measures at the state, regional and national level. Moving pollution sources to city peripheries does not create clean air. **Cleaner air can be achieved in a growing, low-income economy.** Decades of investment have driven down the cost of cleaner energy sources, emission control technologies and energy efficiency. Clean air investments provide economic benefits -- healthcare savings, longer and more productive lives and improved social and development outcomes – with benefits that far exceed costs. **Year-round air quality management is necessary for sustained air quality improvements.** Crisis response to air pollution episodes (i.e. seasonal pollution, forest fire pollution) and Air Quality Index (AQI) notifications are not solutions that sustain air quality improvements. Instead, cities should focus on reducing emission at their sources throughout the year to decrease chronic exposure to air pollutants and the associated adverse health effects.
Air Pollution Data Access	**Open and accessible air pollution data provide multiple benefits.** Government officials benefit from broader dissemination of information to the public, increasing trust and bolstering support for clean air policies. Open data can support access to reliable non-official data and data use for research that feeds back into shaping or evaluating policy. The public gains knowledge of health risks and exposures by time and place.

Table 1h

Practical questions about urban air quality innovation for action

Ambient Air Quality Monitoring	• Why is urban air quality monitoring needed to inform clean air action? • What data on air pollution levels are already available to fill gaps in official monitoring? • What types of information can different types of monitoring innovations provide? • What are the advantages and disadvantages of different monitoring approaches? • How can monitoring approaches and innovations be in phases to provide initial actionable data and build an integrated system of complementary approaches?
Source and Emissions Characterization	• Why is characterization of leading air pollution sources and emissions essential for clean air action planning? • What data on sources and emissions influencing air quality are already available? • What information can different source characterization methods provide? • How can innovative and lower-cost approaches be used to improve local air pollution emissions and source data? • How can different air pollution source assessment methods be used together to evaluate and improve data? • How can emissions and source data help identify local “hot spot” areas, inform air pollution monitor placement and set source control priorities in the near term?
Data Availability and Accessibility	• Why should air pollution data be made open and accessible? • What defines open, accessible air pollution data? • What are barriers to achieving open, accessible data and strategies for overcoming them? • How can reliable air pollution data collected by government and non-governmental institutions be integrated and organized to inform clean air programs? • How can integrated and open-air pollution data benefit a city’s clean air program, researchers and other local data users? • How can air quality data be effectively shared with different stakeholder groups?
Organization for Action	• How can a city organize to develop, implement and sustain clean air actions? • How can strategic policy analyses be used to inform the planning process? • What are key elements of successful clean air action plans in both the near term and the long term?

1

Ambient Air Quality Monitoring

1.1 Introduction: Purposeful, phased use of innovations

Air quality monitoring infrastructure and capacity vary widely among cities. Decades of investment in high-income countries in Europe and North America have established ongoing, high-quality pollution monitoring in nearly all cities, while thousands of cities in rapidly developing low- and middle-income countries lack even a single $PM_{2.5}$ monitor (36). Innovations in monitoring technology, remote sensing and modeling can provide actionable air pollution data more rapidly and at lower cost than conventional regulatory monitoring approaches. However, the explosion in new monitoring approaches, products and data also has the potential to increase complexity and costs, create confusion among the general public, and make it more difficult for governments and citizens to build a shared understanding of a city's air pollution problem and how to address it.

A phased approach to prioritizing innovations to strengthening air quality monitoring can help reduce complexity and avoid monitoring pitfalls, combining conventional regulatory monitoring approaches with innovations. Each local situation is unique and there is no "one size fits all" approach to air pollution monitoring, but a phased approach is recommended to ensure that:

- Monitoring is planned to address specific monitoring goals, questions and data needs.
- The monitoring approaches chosen at each phase are compatible with resources and technical capacity to deploy and maintain equipment and to manage, analyze and use the data being collected.
- Incremental enhancements help build an integrated system of complementary monitoring approaches.
- Governments can make realistic commitments to provide funding, build capacity, sustain air quality monitoring, share air quality data and take meaningful, data-driven actions to control air pollution.

Phases of monitoring capacity described in this chapter are shown in table 1a below. For a given phase, numbered icons through the chapter point to the most relevant chapter content.

Table 1a

Ambient air quality monitoring – capacity phases

1	2	3	4
Limited or none	**Basic monitoring to support initial actions**	**Comprehensive monitoring for sustained actions**	**Advanced integrated system**
No sustained official reference $PM_{2.5}$ monitoring in place	At least one official reference $PM_{2.5}$ monitor in place with ongoing data collection and use (at a minimum for public information)	A network of several reference $PM_{2.5}$ monitors, at least one advanced monitoring station collecting $PM_{2.5}$ sampled for chemical composition and to measure gaseous pollutants. Data have been used in policy development.	Phase 3 monitoring, plus periodic high-spatial-- resolution monitoring

1.2
Monitoring Basics

Relevant Reading for Monitoring Phase

1 2 3 4

What to measure?

Fine particulate matter ($PM_{2.5}$) is the most important pollutant to monitor and reduce. It is an indicator of a pollution mixture[a] that causes the most serious illness and death globally and causes an especially large burden of disease in the most polluted regions and cities (37). In addition to being a proven cause of serious illness and death from cardiovascular and respiratory diseases, cancer and diabetes, which are included in the global burden of disease estimates, $PM_{2.5}$ also impacts birth outcomes and child health, potentially impairing well-being and productivity across the life span (38,39).

Other important pollutants include ozone (O_3), a secondary, regional pollutant, which currently causes roughly one-sixth as many deaths globally as ambient $PM_{2.5}$ pollution (refer to Figure 2b). Nitrogen dioxide (NO_2) is a useful indicator of traffic-related air pollution, a risk factor for asthma development (40) and a pollutant involved in producing ozone (41). Sulfur dioxide ($S0_2$) monitoring is especially useful near sources of coal and high-sulfur oil combustion, which also contribute to $PM_{2.5}$ formation.

Air quality standards

To assess the severity of a local air pollution problem, $PM_{2.5}$ concentrations should be compared to the WHO health-based guideline values, such as an annual average $PM_{2.5}$ level of 10 micrograms per cubic meter (μg/m^3) or a 24-hour average level of 25 μg/m^3**.** Even relatively low concentrations of common air pollutants are harmful to human health (42,43). Based on current evidence, even the WHO guidance for ambient air pollution (3) balances health protection and feasibility, rather than defining a “no effect” level. For highly polluted cities, achieving interim ambient air quality targets, such as those suggested by WHO (44), can mark progress towards meeting a true health-based standard.

For assessing public health risks, chronic exposure, as indicated by annual or seasonal average concentrations, is more useful than short-term exposure, as indicated by 24-hour or hourly concentrations (45). Trends in seasonal or annual average $PM_{2.5}$ concentrations are also better indicators of sustained progress than short-term average concentrations**.** In most cities, short-term air pollution episodes do not cause as much cumulative harm as chronically elevated, but less extreme concentrations. Nevertheless, short-term severe air pollution episodes have serious, acute and potentially lasting health impacts and can increase public and media attention and concern. Public health advisories during such episodes (refer to Chapter 4) can build government credibility and raise support for sustained emission control measures needed to protect health.

a $PM_{2.5}$ has been shown to be harmful to health; additionally, its concentration also is useful as an indicator of harmful ambient air pollution mixtures of many types of particles and gases harmful to health.

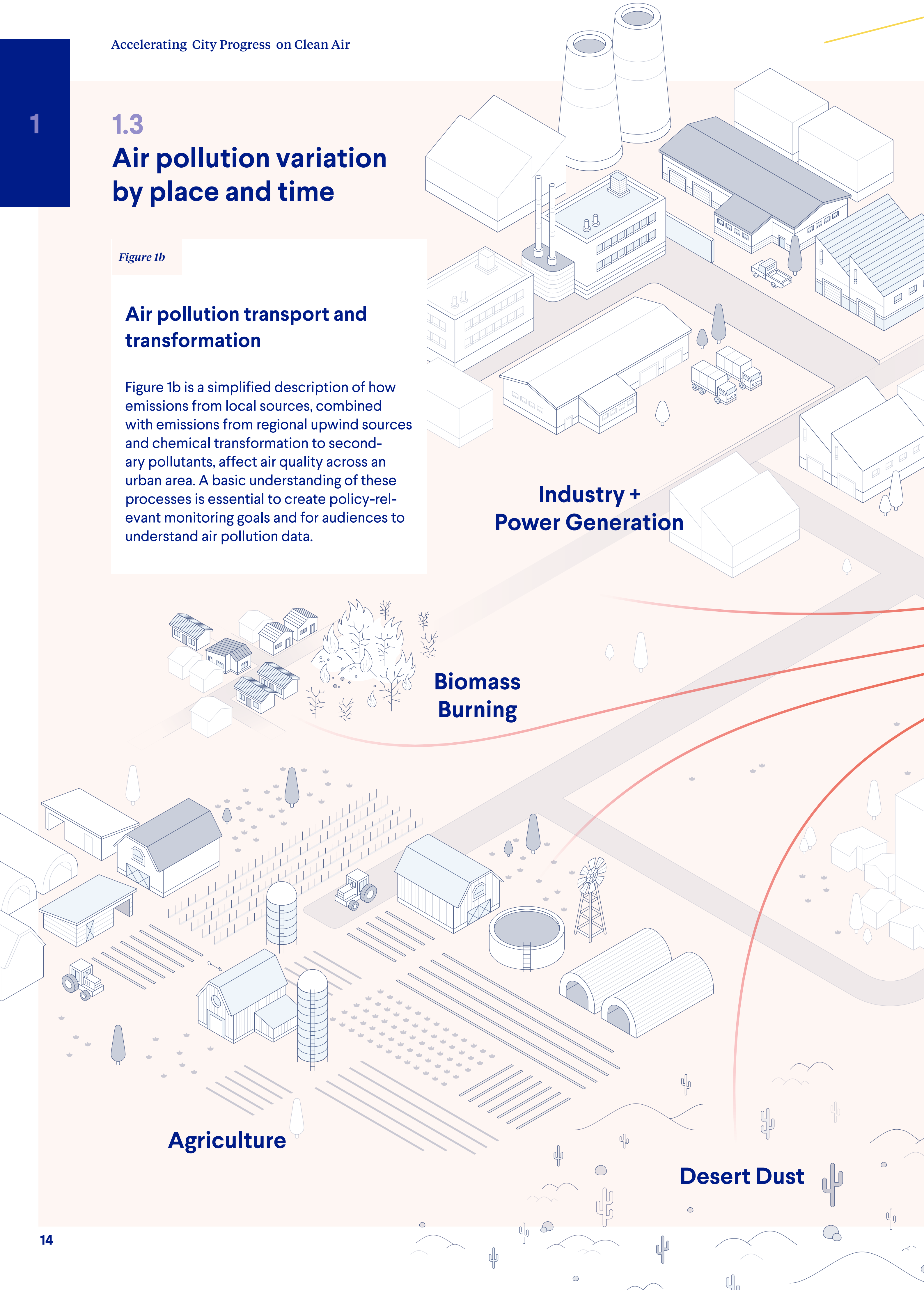
1

1.3
Air pollution variation by place and time

Figure 1b

Air pollution transport and transformation

Figure 1b is a simplified description of how emissions from local sources, combined with emissions from regional upwind sources and chemical transformation to secondary pollutants, affect air quality across an urban area. A basic understanding of these processes is essential to create policy-relevant monitoring goals and for audiences to understand air pollution data.



Some primary air pollutants (e.g. $PM_{2.5}$, oxides of nitrogen, sulfur dioxide, VOCs, ammonia) are transformed in the air to form secondary pollutants, including $PM_{2.5}$ and ozone. Some sources of primary air pollutants are commonly clustered in cities and others are often located outside of cities. Prevailing winds can carry pollutants from regional sources into cities, where they add to local emissions and often cause levels of some pollutants to be higher in cities than surrounding areas. City air pollution is transported by prevailing winds and transformed to influence regional air pollution.

1.3 Air pollution variation by place and time

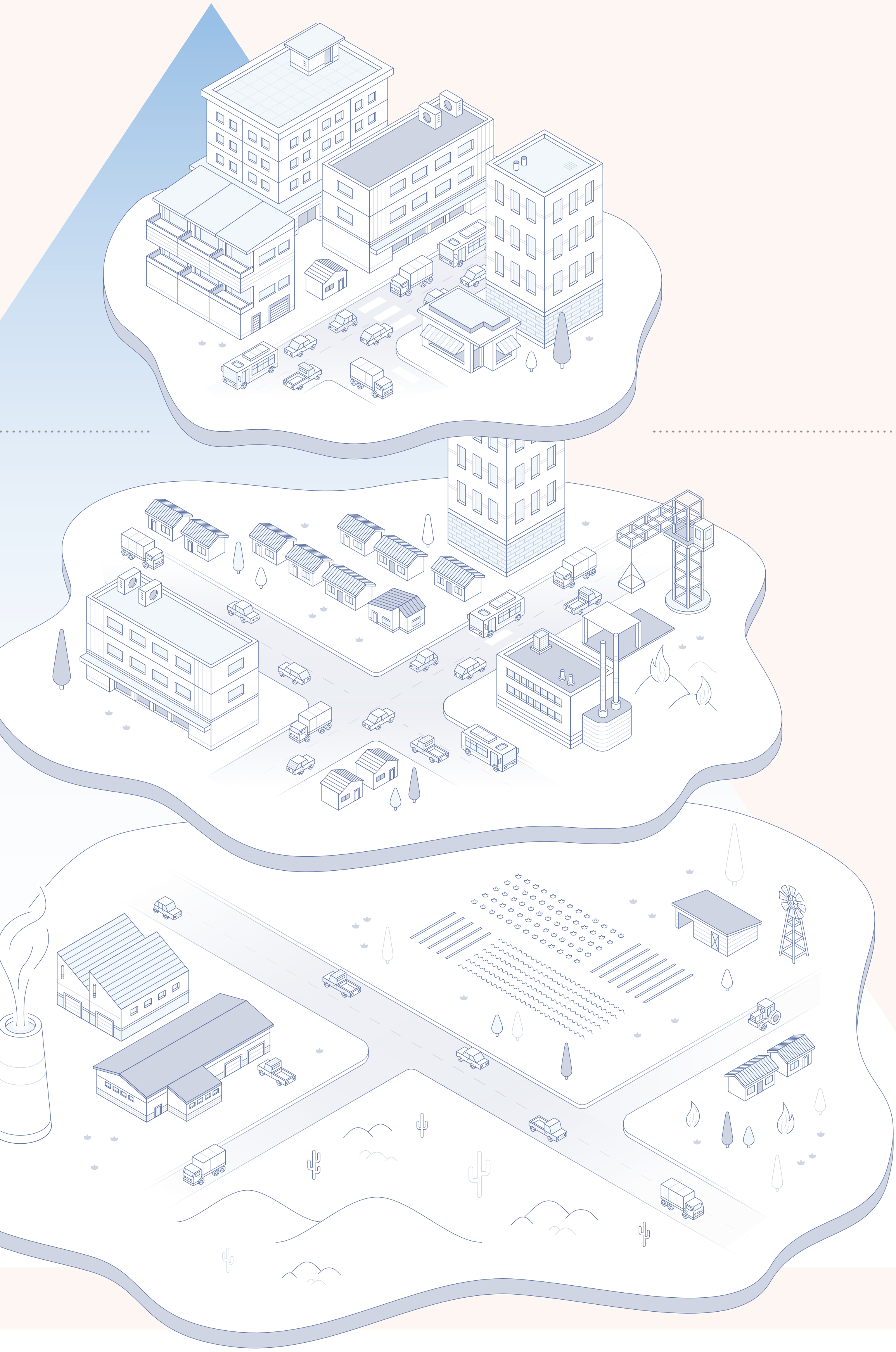
Figure 1c

Air pollution geographic variation, sources and scales for monitoring and action

Regional and transported air pollution contribute to background concentrations in peri-urban areas. The higher density of emissions from sources such as buildings and vehicles across a city often produce higher average air pollution than in peri-urban or rural areas. Within a city, clustering of sources such as vehicles at busy roads and intersections or from heating and cooking in buildings contribute to localized "hot spots" with higher-than-average concentrations of primary pollutants like NO2 and $PM_{2.5}$.

Source: Adapted from IEA, Airparif, available at https://www.iea.org/

Scale for Air Pollution Monitoring	Scale of Clean Air Action Required
Within-City, Hot Spots	Local Neighborhood
Urban Airshed, Average and Trends	Urban/Metro Area
Regional Background	Regional, State and National



Clustered City Sources

City:
Transportation
+ Buildings
+ Trash Burning
+ Construction
+ Etc.

Transported Regional Pollution

1

1.3 Air quality monitoring: Objectives and approaches by phase

An urban air quality program should choose monitoring approaches that fit policy-relevant objectives and questions as well as the program's technical capacity phase.

1

Establish the need and plan for official monitoring, especially for $PM_{2.5}$.

Cities without reliable, official ground-based monitoring can still describe their $PM_{2.5}$ levels. In some cities, high-quality monitors operated by foreign embassies or by researchers can be reliable initial sources of daily, seasonal and average $PM_{2.5}$ measurements. In cities where official monitoring for PM_{10}, but not $PM_{2.5}$ occurs, conversion factors (46–48) can be used to estimate $PM_{2.5}$. A planned low-cost $PM_{2.5}$ sensor campaign, following guidance summarized below, can also be helpful to raise awareness and build support for establishing official, reference monitoring. Satellite-based estimates (refer to Section 2.4) can also be used to estimate annual $PM_{2.5}$ exposure. If ambient $PM_{2.5}$ concentrations derived from one of these sources far exceed health-based standards, work should start (and proceed in parallel) to assess available source data (refer to Chapter 3), identify potential controls (refer to Chapter 5), and initiate or enhance official monitoring.

Key questions to be addressed:

Is the air quality hazardous to health in the urban/metro area?

Why is it important to have reliable official monitoring?

Where should initial reference monitors be placed?

2

Establish and maintain official $PM_{2.5}$ monitoring and plan for monitoring enhancements.

An initial priority for an urban area without reliable ground-based monitoring should be to establish a limited number of fixed reference $PM_{2.5}$ monitors sited to best represent average urban area concentrations. There is no single objective criterion for determining a minimum number of $PM_{2.5}$ monitors needed. Globally, $PM_{2.5}$ monitor density varies widely, from zero to several per million inhabitants (49). In cities with multiple $PM_{2.5}$ monitors, average levels vary from site to site, but this spatial variation within cities can be relatively small (50). Day-to-day changes in ambient $PM_{2.5}$ levels—often influenced by weather—tend to be correlated across monitors within a city and even across an urban region (50,51).

Establishing even one or a few well-placed, high-quality $PM_{2.5}$ monitors in an urban area lacking any monitoring is an important first step to assess the severity of ambient pollution, establish a baseline to track progress, and document unhealthy air quality events for public advisories. Additional, upwind regional background monitoring sites (also known as "contrast" sites) can provide data to compare with pollution levels within cities to help assess regional contributions to urban concentrations. During this phase, scoping and planning for Phase 3 pollutant monitoring objectives should begin.

Key questions to be addressed:

What is the baseline $PM_{2.5}$ level and trend as clean air actions are launched?

When are short-term air pollution episodes occurring?

b US EPA guidance recommends that urban scale $PM_{2.5}$ monitors be › 1 km away from large polluting facilities and more than 100 meters from busy roadways.

1.3 Air quality monitoring: Objectives and approaches by phase

3 Monitor $PM_{2.5}$ composition and additional pollutants, increase monitor coverage.

Limited initial monitoring can demonstrate the need for action, but more comprehensive monitoring is needed to better assess $PM_{2.5}$ sources, space and time variation, and to measure other harmful pollutants. Advance surface particle monitoring stations provide temporally resolved $PM_{2.5}$ measurements and $PM_{2.5}$ chemical composition data from time-integrated samples (refer to section 2.4). These are useful for receptor-based source apportionment analysis (refer to Chapter 3). At least one advanced surface particle monitoring station should be considered in each distinct airshed within any region of interest. Airsheds are commonly defined by geographic/topographic and meteorological regions.

A phase 3 monitoring network should include one or more locations where all common gaseous pollutants are measured, including those involved in ozone and secondary particle formation: oxides of nitrogen (NO_x), sulfur dioxide (SO_2), carbon monoxide, ozone and volatile organic compounds. The temporary deployment of a network of reliable low-cost sensors, as well as enhanced spatial resolution methods described in phase 4 should be considered to inform monitor site locations.

Key questions to be addressed:

- What are important sources of urban/metro area air pollution?
- Are control measures improving air quality in the urban/metro area?
- Where should additional monitors be placed?

4 Enhance spatial resolution within the urban area with an advanced, integrated system.

Having established a reliable urban-scale air quality monitoring system that can track progress on clean air measures that address multiple pollutants, a useful next step is improving spatial resolution using periodic mobile monitoring campaigns and/or land use regression (refer to section 2.4) or dispersion models. When combined with temporal patterns from conventional ambient monitors within the airshed, high-resolution spatiotemporal estimates can be produced in near real time.

While low-cost sensor networks (refer to section 2.4) at present are unlikely to directly replace such estimates, their deployment can be informed by the spatial and temporal air quality patterns. Once calibrated to the conventional air quality monitoring stations, low-cost sensor data could be used to identify deviations from the estimates and generate hypotheses about new or changed source activity or land-use changes for further investigation through field visits and additional focused monitoring campaigns. In turn, the sensor networks can inform

Key questions to be addressed:

- What are the local neighborhood hot spots and sources?
- Are control measures improving local neighborhood air quality?

improvements in the estimates of pollution concentrations and the need for additional high-quality monitor sites, and suggest when mobile monitoring campaigns or modeling exercises should be repeated.

Figure 1d
Strengthening monitoring: a phased approach

1	2	3	4
Is the air quality hazardous to health in the urban/ metro area? Why is it important to have reliable official monitoring? Where should initial reference monitors be placed?	What is the baseline $PM_{2.5}$ level and trend as clean air actions are launched? Is local air quality compliant with local standards? When are short-term air pollution episodes occurring?	What are important sources of urban/ metro area air pollution? Are control measures improving air quality in the urban/metro area? Where should additional monitors be placed?	What are the local-neighborhood hot spots and sources? Are control measures improving local-neighborhood air quality?
Satellite-based estimates Non-official reference $PM_{2.5}$ monitoring Land-use regression, low-cost sensor, or mobile monitoring studies	**Phase 1+** One or more fixed reference $PM_{2.5}$ monitors	**Phase 2 +** Advanced surface particle monitoring station One or more reference monitoring station for gaseous pollutants	**Phase 3+** Periodic land-use regression models or mobile monitoring campaigns Low-cost sensor network

Increasing monitoring devices and network density →

1.3
Air quality monitoring: Objectives and approaches by phase

The phased approach suggested above is not meant to be prescriptive, and the sequencing and specific technology used will depend on local context, budget and capacity. For example, high-spatial-resolution methods, including low-cost sensor networks that may already exist in some communities, can help to raise public awareness about air pollution and build confidence in official monitoring that accounts for known spatial gradients and sensitive populations. The important principle is that monitoring is aimed at answering questions and providing actionable data and contributing to developing an integrated, sustainable system.

Across all monitoring phases, a range of approaches, including high-spatial-resolution monitoring studies, emissions mapping and satellite-remote-sensing-based estimates, can help identify priority locations for additional fixed reference monitors (refer to Figure 1d). Ground-based monitors can be deployed with higher density in areas of greater variability, weighted towards areas with higher population density and in locations where rapid growth in emissions is anticipated, such as near industrial parks. This approach also facilitates modeling and forecasting at regional and urban scales with a goal of providing temporally and spatially resolved accurate estimates of concentrations as well as regional and local source contributions.

1

1.4
More about monitoring approaches: Conventional and innovative

Costs, people, infrastructure and logistics

Detailed guidance on costs and resource needs for different monitoring approaches are beyond the scope of this guide. For more information on this topic, readers may refer to a summary of a 2017 World Bank conference (36). Some key costs to consider are:

- Purchase price of monitoring equipment
- Supplies, parts, service and shipping for repairs and maintenance
- Consumables, shipping, laboratory analysis for filter-based or passive gaseous sampling
- Structures and supporting infrastructure
- Property leases if applicable
- Utilities including reliable electric power and wireless communications
- Personnel costs for deployment, calibration and maintenance
- Data management equipment, fees and personnel

Relevant Reading for Monitoring Phase

1 **2**

Conventional, fixed-location reference monitoring

Conventional reference monitoring stations typically incorporate robust, high-quality devices to provide a combination of real-time or integrated average measurements of common air pollutants such as sulfur dioxide (SO_2), carbon monoxide (CO), Nitrogen Dioxide (NO_2), PM_{10} and/or $PM_{2.5}$ and O_3. Monitoring networks should prioritize $PM_{2.5}$ as a better health risk indicator than PM_{10}.

Conventional, regulatory air quality monitoring has focused on establishing a usually limited number of fixed-location reference-method monitors sited to provide information on regional- or urban-scale concentrations and trends. Concentrations are compared to regulatory ambient air quality standards or health-based guidance levels. Fixed location monitors can also be placed at targeted locations to assess the impacts of specific sources such as motor vehicles, industrial sources or power plants.

Conventional reference monitoring stations are relatively costly to establish and maintain considering unit instrument costs, site requirements of shelter, reliable power supply and climate control, and substantial ongoing servicing by trained personnel for calibration, filter changes and other maintenance. As a result, reference monitor density is often limited, even in high-income countries. Nonetheless, as noted above (cross-reference phase 2) even one or two reference monitors can demonstrate and track poor air quality in an urban area. Investments in reference monitors should be consistent with resources for sustained operation. In some low-income countries, high maintenance and personnel requirements have sometimes resulted in conventional regulatory monitoring equipment ceasing to function reliably within just a few years of installation.

1.4 More about monitoring approaches: Conventional and innovative

Innovative approaches

Building a robust official ground monitoring network using fixed reference monitors should be part of a goal of urban air quality management programs, but innovative approaches, strategically deployed, can accelerate the collection of actionable air quality data (52).

Relevant Reading for Monitoring Phase

1 2 3 4

Satellite remote sensing-based monitoring

Satellite remote sensingbased monitoring can fill gaps in ground monitoring and has become a critical source of global air quality information (53). Satellite remote sensing-based estimates now provide a standardized measure with complete global coverage suitable for evaluation of trends since approximately the year 2000 and for estimating the global burden of disease. National and in some places, state- and urban-area-level estimates of ambient $PM_{2.5}$ and ozone concentrations and the current health burden from air pollution are freely available for all countries online (54–56). While not a substitute for on-ground monitoring, satellite remote sensing estimates are sufficient to demonstrate the need for improving air quality in highly polluted cities. Remote sensing estimates require specialized technical skills to analyze and interpret; most cities seeking to use remote sensing estimates will need training or technical partners with this capability. More detailed information and references are provided in **Annex 1, 2 and 3**.

Relevant Reading for Monitoring Phase

2 3 4

Advanced surface monitoring

Advanced surface monitoring stations provide information on additional pollutants (e.g., hazardous or toxic air pollutants like benzene) and $PM_{2.5}$ chemical composition (52). One example is the advanced monitoring stations deployed by the US $PM_{2.5}$ Chemical Speciation Monitoring Network (CSN) (57). Speciation is a method for identifying the specific chemical mix in air pollution that is useful for identifying the most important contributing sources (refer to Chapter 3). Another example is the Surface Particulate Matter Network (SPARTAN), which is a network of 19 active sites worldwide that provide publicly available data on $PM_{2.5}$ mass and chemical composition. Unique features of SPARTAN include co-location with sun photometers for Aerosol Optical Depth measurement (58,59) to support the improvement of satellite-based estimates of local $PM_{2.5}$ and a centralized, advanced laboratory for chemical composition analysis (58,59). SPARTAN devices can operate for 63 days unattended between filter cartridge collection.

Lower cost, filter-based PM monitors [e.g., MiniVOL sampler (Airmetrics)] or passive gaseous samplers, which measure time-integrated pollutant concentrations without using pumps, can be used in time-limited campaigns. More detailed information and references are provided in **Annex 1.**

1

1.4 More about monitoring approaches: Conventional and innovative

Relevant Reading for Monitoring Phase

3 4

High-spatial-resolution or "hyperlocal" monitoring—identifying urban "hot spots"
As noted above, conventional monitoring networks are not designed to characterize the true spatial variability in pollutant concentrations within urban areas. Knowing how pollutant concentrations vary within a city is important for identifying how sources vary across a city, and for mobilizing communities to support clean air actions (60,61).

Spatial gradients in NO_2, black carbon, CO and in some locations SO_2 are generally more pronounced and better indicators of local emission sources than $PM_{2.5}$ and O_3.

Three approaches (sometimes used in combination) to characterize spatial variation in pollutant levels at high (~100m) resolution are summarized below. These lower-cost approaches for characterizing spatial variation could be useful for informing and evaluating geographically localized interventions, such as low emission zones, and for guiding the placement of more expensive fixed site monitors within an urban area. Refer to **Annex 2** for more details and references about each method.

Land use regression modeling has revolutionized understanding of air pollution variability within urban areas and become increasingly the norm for epidemiologic investigations of long-term exposure to air pollution (62). In this approach, measurements are collected over temporary but defined periods at a relatively high number of locations within an urban area. Monitoring results are combined with geospatial data describing air pollution sources or their proxies to estimate highly spatially resolved annual or seasonal air pollutant concentrations. Land use regression studies require technical capacity that typically will require collaboration with academic researchers or other partners.

Mobile monitoring is an approach in which high-quality instruments that detect one or more pollutants of interest are deployed in one or more vehicles to collect measurements while repeatedly driving a planned route. Measurements are analyzed to map air quality—especially for primary pollutants with strong spatial gradients, such as NO_x, black carbon and ultrafine particles (UFP)—at high spatial resolution throughout urban areas. Mobile monitoring could be helpful in identifying small but poorly controlled local emissions sources of these pollutants. In contrast, mobile monitoring may be less useful for characterizing pollutants that vary less over small areas (e.g., $PM_{2.5}$, O_3).

Relevant Reading for Monitoring Phase

1 2 3 4

Low-cost sensors
Low-cost sensors are a promising innovation with many applications, particularly when integrated with other modeling approaches. A recent surge in interest and development has produced commercially available devices for the consumer market (63). Low-cost sensors have been utilized by citizen groups when government measurement data have been unavailable or considered unreliable. One low-cost sensor application is in a network with large numbers of devices, densely deployed to assess changes in pollutant concentrations over small spatial areas and short time periods (64).

1.4 More about monitoring approaches: Conventional and innovative

Low-cost sensors have important limitations (65, 66) that should be considered when determining how they should be used and what questions they can answer. Several testing and evaluation programs for specific sensors as well as guidance on how they should be deployed in networks describe reliability, validity and logistic considerations. These programs have found that some devices when used in the field yield concentration estimates that are very close to those from reference monitors while many others are very poor predictors of actual air quality. Because so many devices are quickly coming to market, an independent evaluation of their validity cannot always be counted on (67) (64,68–71). A useful summary of the best practices to guide the selection of low-cost sensors has been published by the World Meteorological Organization (64) (refer to **Annex 2**).

As government data quality and availability improve and increasingly meet citizen goals for accessible air quality information, the demand for citizen-based sensors and networks to fill data gaps may decline, but their applications in citizen-science partnerships, engagement and awareness-raising will likely remain.

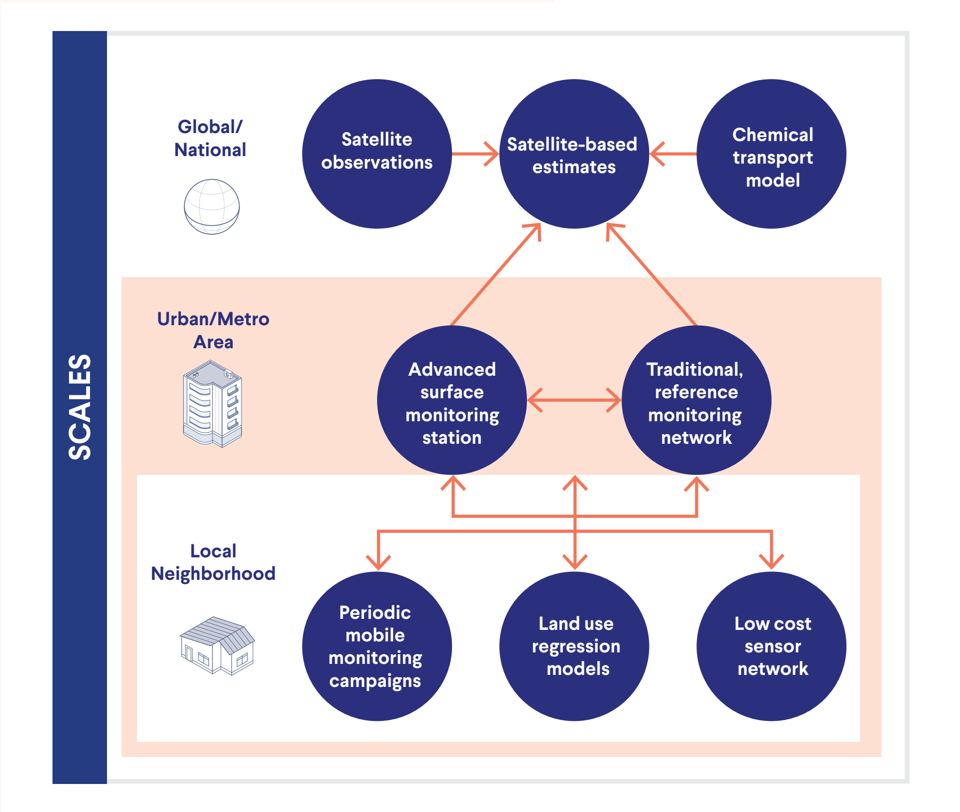
1

1.5
An integrated system combining conventional and innovative approaches

Relevant Reading for Monitoring Phase
2 3 4

The complementary conventional and innovative approaches and the phased approach described above can be used to build an integrated system for each urban airshed (Figure 2e). A combination of approaches can inform a robust air quality management program, support the needs of local, regional and national air quality management, and provide data for research and public information (49). The cost of deploying and operating such a system will vary greatly depending on local circumstances (refer to **Annex 1**) but would likely be much less than a conventional regulatory network with many reference monitors.

Figure 2e
Integrated air pollution monitoring system



Depicted is a framework for using satellite remote sensing methods, traditional and advanced surface monitors and periodic monitoring with one or more high spatial resolution approaches: land-use regression, mobile monitoring or low-cost sensor networks. Such a system can assess air pollution variation at different spatial and temporal resolution, inform additional reference monitor placements and incorporate new innovations over time.

City case studies of monitoring innovations in action:

New York City

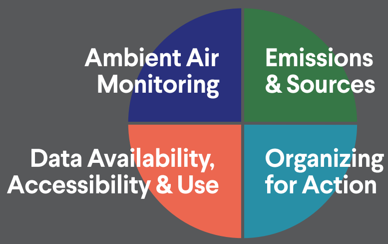
Oakland

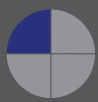
London

2

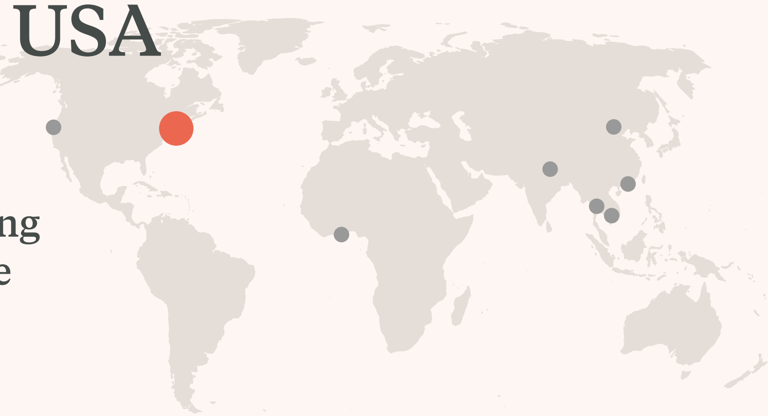
Case Studies

Summary of case studies of monitoring innovations in action



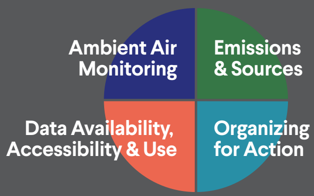
City	Innovations Applied	Actions
New York City, USA		Phase out high-sulfur heating oil
Oakland, USA		High-spatial-resolution mapping of air pollution in urban areas
London, UK		Integrated, hyperlocal air pollution mapping and monitoring

New York City, USA



A transition to cleaner heating fuels informed by innovative monitoring, emissions data and modeling

Innovations Applied



New York City (NYC) has the highest population (more than 8.6 million in 2017) and population density of any city in the United States (179). While once home to many industries, the economy of NYC today as measured by employment is dominated by service sectors, including health and education, information technology, retail, finance, real estate, leisure and hospitality (180). After experiencing population stagnation and decline from the 1960s through much of the 1980s, NYC population has grown steadily, increasing more than 5% since 2010.

Primary stakeholders involved in New York's effort for air quality improvement

- **Government ministries** (e.g., NYC Department of Health)
- **Technical partners and advisors**
- **Legal and policy advisors**

The Issue

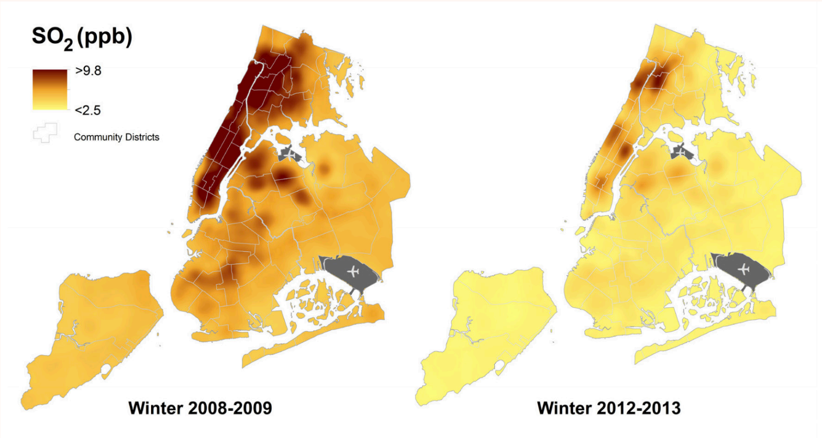
The air quality in NYC had been improving as of 2007, with $PM_{2.5}$ levels close to reaching the National Ambient Air Quality Standards (NAAQS) since 2000 (181). However, air pollution remained one of the most signficant environmental threats to NYC residents, contributing to about 6% of premature deaths annually (182).

NYC's regulatory air monitoring system, managed by the New York State Department of Environmental Conservation, conformed to national standards to support the state's legal requirement to develop programs to achieve NAAQS. The monitoring system included 22 $PM_{2.5}$ monitors, but only three for monitoring the gaseous pollutants sulfur dioxide (SO_2) and oxides of nitrogen (NOx) across the roughly 780-square-kilometer city, which was too sparse to identify local pollution hot spots and emissions sources (181).

Enhanced Local Monitoring Identifies a Major Pollution Source

In 2007, NYC launched its first multisectoral long-term environmental sustainability plan, known as PlaNYC, for improving the city's major infrastructure systems, natural environments and environmental indicators. PlaNYC included a number of air quality initiatives, with a goal of achieving the "cleanest air" of any large city in the United States (183). Given the limited spatial coverage of NYC's existing air monitoring system, the city's department of health launched more geographically intensive pollution monitoring under PlaNYC known as New York City Community Air Survey (NYCCAS) in 2008 to assess spatial

Estimated SO_2 concentrations, winter 2008-2009 and winter 2012-2013



Source: New York City Trends in Air Pollution and its Health Consequences, Sept 2013 Report, available at https://www1.nyc.gov/assets/doh/downloads/pdf/environmental/air-quality-report-2013.pdf

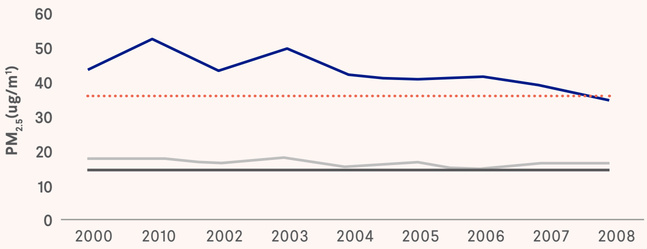
variation in air pollution across neighborhoods, identify important local sources and inform local clean air measures. NYCCAS deployed a spatially dense network of 100 to 150 integrated samplers—designed by a local university partner—to measure major pollutants. Data from the samplers were analyzed along with co-located regulatory monitors to validate measures and adjust for temporal variation. The data were then combined with GIS data on indicators of local emissions from traffic, buildings and other sources in land-use regression models that estimated spatial variation in pollution across the city (184).

The survey found a strong association between average concentrations of SO_2 and nickel in fine particulate matter ($PM_{2.5}$) and the number of building boilers burning high-sulfur oil within one kilometer of the sample location during the winter of 2008-2009, suggesting high-sulfur heating fuel to be a major source of neighborhood air pollution (185,186). At the time, an estimated 10,000 NYC buildings burned the dirtiest heating fuels (i.e., #4 and #6), which produced higher emissions of both SO_2 and $PM_{2.5}$. These buildings—just 1% of all buildings in the city—caused similar $PM_{2.5}$ emissions as all on-road vehicles citywide (187).

Improving Local Emissions and Modeling

A subsequent health impact assessment used refined and spatially allocated emissions data—which were updated by the NYC tax data on building size and boiler fuel type environmental permit data—to better reflect the locations and quantities of heating oil use. The assessment used atmospheric modeling

Trend of annual ambient $PM_{2.5}$ concentrations in New York City between 2000 and 2008



Maximums shown are the 58th percentile 24-hour $PM_{2.5}$ concentration and the fourth highest daily maximum eight-hour ozone concentration within a year.
Source: US EPA Air Quality System (AQS)

24 Hour Maximum Concentration
Annual Average Concentration
24 Hour Regulatory Standard
Annual Regulatory Standard Concentration

Source: US EPA Air Quality System

to estimate reductions in $PM_{2.5}$ at 1 kilometer resolution, health benefits from clean heat changes through 2013, and further benefits from completely phasing out high-sulfur heating oil ahead of the 2030 deadline (188). Compared to a business-as-usual scenario with 2008 heating oil use, the study estimated that a complete phaseout of high-sulfur heating oil could avoid annual health impacts of 290 premature deaths, 180 hospital admissions for respiratory and cardiovascular emissions and 550 emergency department visits for asthma.

Organizing for Clean Air Actions

Findings from NYCCAS helped to spur local and state regulations and laws that required a phase-out of #6 heating oil by 2015, of #4 heating oil by 2030 and a reduction of sulfur content in #2 and #4 oil in 2012 (188). Conversions to cleaner heating fuels began in anticipation of these deadlines, aided by falling

Exhaust from a boiler using high-sulfur heating oil.

Source: https://www.nyccleanheat.org/content/problem
Photo Credit: Patti McConville

natural gas prices and a city program to assist building owners in planning conversions. By 2013, winter SO_2 concentrations had fallen by 69%, while nickel concentrations declined by 35% (187).

The mayor of NYC established an Office of Long-term Planning and Sustainability as part of the PlaNYC process to convene multiple city agencies, coordinate their activities and establish systems for tracking and reporting progress on implementation of many sustainability programs. Resulting funding established a new air pollution monitoring and epidemiology program integrated with an environmental health surveillance with several technical staff positions and academic partnerships. The mayor's leadership promoted cross-agency collaboration facilitating the clean heat program and other clean air actions that he championed. After the impact of local high-sulfur heating oil based on monitoring data from the health department was established, boiler permits from the Department of Environmental Protection and building size data were used to better spatially allocate heating emissions data in support of bottom-up emissions source apportionment modeling. Partnerships across agencies led to further clean air and climate action policy initiatives. The improvements in monitoring, emissions data and modeling capacity have also helped to inform other local policy initiatives including a revision of local air pollution regulations. This makes NYC the first jurisdiction in the United States after California to require controls to reduce commercial charbroiling $PM_{2.5}$ emissions, conduct a health impact analysis of heavy duty diesel vehicles, monitor other exposures including air toxics, noise and pollen, and exposure estimation for health studies (189–192). NYCCAS monitoring data and modeled pollution estimates were made available through open data portals and for researchers. In 2015, a local law was passed mandating the continuation of NYCCAS.

Lesson learned

NYC's effort to convert to cleaner heating fuels was informed by innovative monitoring, improved emissions data and modeling capacity. NYC's effort highlights the importance of political leadership, convening and coordination across multiple agencies; data-driven policy and implementation follow-through; and open data access that engaged stakeholders to support continued air quality monitoring.

Oakland, California, USA

Experience on high-spatial-resolution mapping of air pollution in urban areas

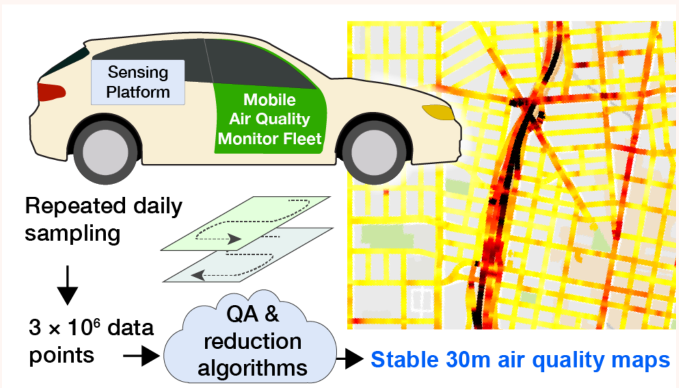
The city of Oakland is one of the most populated cities in California, with 431,000 residents in 2018 (193). Once known for its harbor and deep-water port, Oakland now has a highly diversified economy and is home to several major corporations (194,195). The major industries in Oakland as measured by employment are professional, scientific, and technical services, health care and social assistance, educational services, retail trade, construction, and manufacturing (196).

Primary stakeholders involved in Oakland's effort for air quality improvement

- Technical partners and advisors
- Private companies

The Issue

Air pollution concentrations, especially ultra-fine particles, nitrogen monoxide, and black carbon, can vary dramatically over a short distance within an urban area due to unevenly distributed emissions sources, dilution, and physiochemical transformations (197,198). However, most ground-based air quality monitoring networks, which are used to provide information on urban-background pollution concentrations, often do not adequately capture the spatial variability in pollution exposure in urban areas. Even in high-income countries, routine monitors are generally sparsely sited. In the U.S. there is a mean of ~two to five routine air quality monitors per million people and 1,000 km2 (197). Given that air quality measurements are necessary for air quality management and public health protection, an alternative monitoring approach is needed to provide the high spatial resolution needed to characterize heterogeneous human exposures and localized air pollution hot spots.



Approach of air pollution measurements in Oakland, California using two specially equipped Google Street View cars.

Source: available at https://apte.caee.utexas.edu/google-air-mapping/

2

Enhanced Ambient Air Monitoring

A new approach was developed using specially equipped Google Street View cars to identify urban air pollution patterns in a 30-km2 area of Oakland at very fine (~30 m) scales, at four to five orders of magnitude greater spatial precision than possible with current fixed site ambient monitoring (197). The mobile monitoring campaigns focused on three socioeconomically diverse neighborhoods within Oakland: West Oakland (a lower-income neighborhood near the port of Oakland and industries; ~10 km2), Downtown Oakland (a mixed residential and commercial mid- and high-rise buildings; ~5 km2), and East Oakland (a neighborhood with industrial and mixed-income residential areas; ~15 km2).

Mobile monitoring was conducted for about six to eight daytime hours on the designated routes of the different neighborhoods on every weekday for over one year, collecting more than 3 million data points and logging over 15,000 miles (199). A fast-response pollution measurement platform on each Google car repeatedly sampled the concentrations of black carbon particles, nitrogen oxides (NO), and nitrogen dioxide (NO2). The resultant maps of annual daytime air pollutant concentrations at high-resolution scale show highly variable air pollution concentrations by as much five to eight times within an individual city block, and air pollution levels in many streets inside neighborhoods where small, consistent pollution hot spots (e.g., traffic congestion, industrial and cooking emissions) are present.

Multipollutant hotspots identified from BC median concentrations measured using the Google Street View cars in Oakland, California.

Source: Apte JS, Messier KP, Gani S, et al. High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data. Environ Sci Technol. 2017;51(12):6999-7008. doi:10.1021/acs.est.7b00891

A Google Street View Car mapping the streets

Organizing for Clean Air Actions

The availability of high-resolution air quality data in Oakland has important implications for epidemiology, as the spatially resolved exposure estimates can reduce exposure measurement error that may bias the health effect estimates. An epidemiological analysis using the high-resolution street-level air pollutant measurements confirmed that traffic pollution affects cardiovascular health, adding evidence to support reducing exposures in urban areas and neighborhood hot spots in Oakland (200). In addition, the high-resolution air quality maps are proposed to be used as an indicator for the assessment of environmental equity in the Downtown Oakland Specific Plan to address disparity and promote health (201). Actionable data from the campaign are also being used to inform the new Seaport Air Quality 2020 and Beyond Plan on emissions reduction measures (202), and to advocate for cleaner air under California's landmark AB 617 law, which develops a new community-focused program to more effectively reduce exposure to air pollution and protect public health (203).

Lesson learned

Oakland's experience in high-resolution air quality data mapping using mobile monitoring campaign complements the existing monitoring network of fixed site ambient monitoring by filling the important data gaps regarding localized pollution hot spots and enabling targeted pollution reduction and control measures.

London, United Kingdom

Hyperlocal air quality monitoring project for measuring and mapping air pollution

Millions of Londoners face health threats every day because of air pollution. London's toxic air has an economic cost of £3.7 billion every year, due to the health impact of pollutants like $PM_{2.5}$ and NO_2 leading to lost years of life, hospital admissions and deaths. Some people are especially vulnerable to the dangers of air pollution – including children, the elderly, people of colour, low-income communities and those with diabetes, heart disease or respiratory problems. These groups may suffer an increased risk of developing cardiovascular disease, cancer, asthma and other respiratory diseases; or of worsening conditions that are already present.

Primary stakeholders involved in London's effort for air quality improvement

- Government ministries (i.e. Mayor of London)
- Technical partners and advisors (Environmental Defense Fund Europe, ACOEM Air Monitors, Cambridge Environmental Research Consultants, Google Earth Outreach, the National Physical Laboratory, University of Cambridge, the Environmental Research Group at Imperial College London (formerly King's College London))
- Advocates and civil society organizations (e.g. C40 Cities)

London has breached legal limits for air quality every year since implementing them in 2010, and all of London's boroughs fail both annual targets and World Health Organization standards. Mayor Sadiq Khan in 2019 declared air quality a 'public health emergency' and has prioritised tackling the health issue, but additional actions are needed to ensure the city meets the World Health Organization's clean air guidelines.

Project overview

To better understand Londoners' exposure to air pollution, the Breathe London pilot project combined state-of-the-art monitoring technology with new methods of data analysis. By measuring harmful pollution across London and at thousands of locations, especially at a local level, the project informed data-driven solutions to clean London's air and foster healthier, stronger communities.

The pilot phase of the Breathe London project was delivered by a consortium led by Environmental Defense Fund Europe (EDF Europe) and funded by the Children's Investment Fund Foundation, with continued funding from Clean Air Fund. Further funding support was provided by the Valhalla Charitable Foundation for EDF staff, as well as additional funding by the Mayor of London for the wearables study and hospital pods. The pilot project was convened by C40 Cities, the leading global alliance of cities committed to addressing climate change, and the Mayor of London. The pilot phase ran from July 2018 to November 2020.

Stationary Network
100 sensor pods, installed on lamp columns and buildings across the city, continuously transmitted air quality measurements.

Mobile Mapping
Specially-equipped Google Street View cars used mobile sensors to measure air pollution on a variety of roadways, taking readings approximately every second.

Wearables
Specially-designed backpacks with air quality sensors allowed children and teachers to monitor air quality during their journey to and from school.

With cutting-edge sensor technology and research, Breathe London comprised three projects that brought new understanding of air pollution levels where people live, work and play:

The main aims of the pilot project were threefold:

- Advance the use and development of innovative, lower-cost monitoring techniques to support cities around the world;
- Enhance London's existing regulatory network to better understand pollution and assess targeted solutions for cleaner air, like the Ultra Low Emission Zone; and
- Make air pollution data publicly available and visualise it in new and innovative ways.

Findings

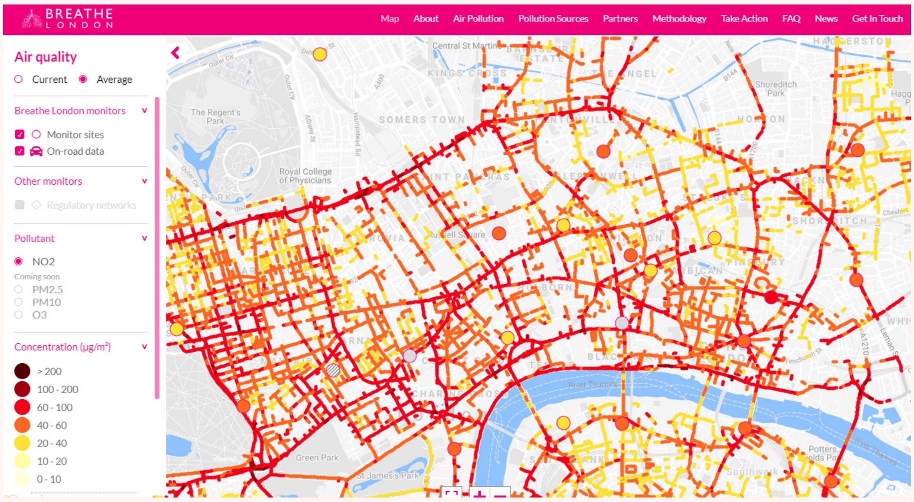
The city has a well-established regulatory network of higher-cost, stationary, continuous air quality monitors used to assess compliance with legal standards, which served as an excellent reference network to study the reliability and accuracy of the lower-cost sensors deployed as part of Breathe London. Validating lower-cost methods of measurements against such a network was an important goal of Breathe London in order to support replication in other cities interested in using lower-cost air quality sensors.

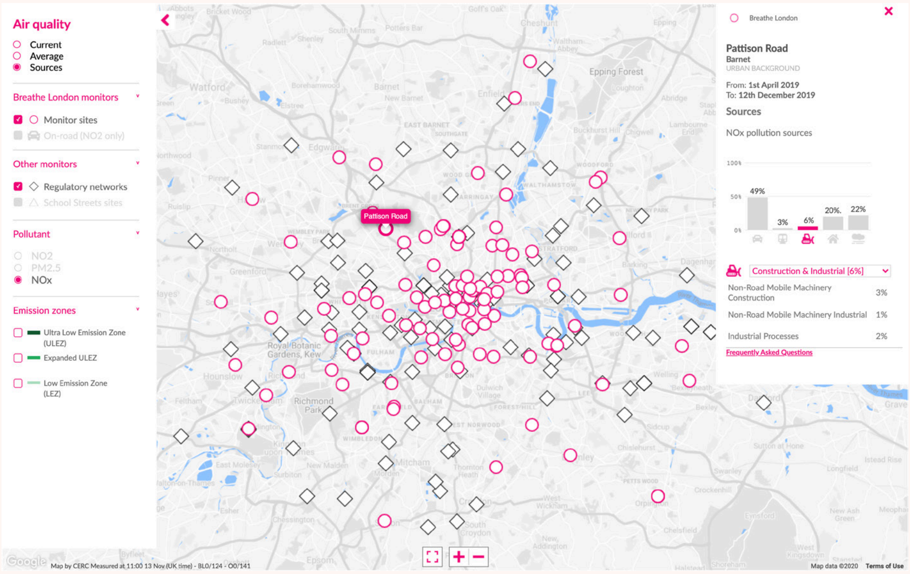
Breathe London developed openly shared quality assurance and quality control (QA/QC) procedures and analysis algorithms, and demonstrated how to effectively leverage lower-cost and new monitoring techniques. It enabled the assessment of pollution hotspots and the evaluation of policy interventions through a network of 100 stationary sensors, combined with repeated mobile monitoring on nearly 600 kilometres (km) of varied roads, to measure and map air pollution across Greater London. Policymakers and community groups were able to use Breathe London data to better understand local pollution and its sources.

In its first year, Breathe London monitoring spanned the months leading up to and immediately following the implementation of the world's first Ultra Low Emission Zone (ULEZ) in Central London and in its second year, the extended operation of the stationary network captured the unprecedented times of COVID-19 and the air quality effects of restrictions that ensued.

Breathe London also created a robust, open-access, hyperlocal dataset that generated an unprecedented level of detail about air quality in London. The team made the data available to the public on the Breathe London platform (right), which showcased an interactive map with real-time and historical measurements.

Source apportionment results from modelled emissions scenarios were added to the Breathe London platform to display hyperlocal pollution sources data alongside current pollution measurements on the interactive map. The feature enabled anyone interested in learning more about how different activities contribute to local NOx pollution, such as road transport, to explore data at all Breathe London and regulatory monitoring sites.





Interactive maps of air quality data are publicly available https://www.globalcleanair.org/data-to-action/london-uk/

Lessons learned

Breathe London data produced insights that were broadly comparable to findings from London's extensive regulatory network, demonstrating that lower-cost sensor systems and mobile monitoring are valid options for generating useful data.

Even if a city only has limited access to regulatory air quality monitors, you can assess a city's pollution and meet different goals, including finding pollution hotspots, measuring how well an intervention is working and raising public awareness.

EDF Europe is producing a Breathe London Blueprint that will be disseminated broadly in early 2021 in order to share these lessons with other global cities and support future hyperlocal monitoring initiatives.

A

Annexes

A

Annex 1
Air quality monitoring innovations

Relevant Reading for Monitoring Phase

1 2 3 4

Satellite remote sensing-based estimates fill gaps in ground monitoring

Satellite remote sensing has been a critical source of global air quality information (1), especially in locations without any ground monitoring. This approach can also fill data gaps in areas with extensive ground monitoring (2–5). When combined with chemical transport models to relate atmospheric column measurements to surface concentrations, satellite-based estimates are available at varying spatial resolution (~1-10 km) for all common air pollutants ($PM_{2.5}$, NO_2, CO, SO_2) except for ozone; these estimates are increasingly used to estimate exposure in studies demonstrating health effects of chronic exposure (e.g., Li et al., (6)).

Satellite remote sensing-based estimates now provide a standardized measure with complete global coverage suitable for evaluation of temporal trends since approximately the year 2000 and for estimating the global burden of disease. National and in some places, state-level estimates of ambient $PM_{2.5}$ and ozone concentrations and the current health burden from air pollution are freely available for all countries online and can be compared to the impact of other risk factors (7,8). Future enhancements to satellite remote sensing technology and capabilities are planned [e.g. MAIA (9)]. Additionally, use of near-real-time data streams from geostationary satellites focused, for example, on India (vs. the current polar-orbiting satellites that provide snapshots one to two times per day) could provide further information to enhance public communications, forecasts and source analysis.

A key limitation of satellite-derived estimates is the lack of information during periods of cloud and at night. In addition, satellites measure pollution in the entire column or air between the earth's surface and the satellite, rather than surface levels needed for air quality management. In the case of PM, satellites measure the amount of reflected sunlight scattered by PM in this entre column, a measure known as Aerosol Optical Depth (AOD). AOD is typically related to surface PM concentrations by simulating this relationship with a chemical transport model. Linking ground-based measurements of AOD via a sun photometer with measurements of $PM_{2.5}$ can help improve simulations, correct for potential biases and improve the accuracy of satellite-based estimates from both global and regional perspectives.

Because of gaps in on-ground monitoring, it is true that "No one knows which city has the highest concentration of particulate matter" (10). However, satellite remote-sensing based monitoring increasingly makes it possible to confidently identify urban areas with average ambient $PM_{2.5}$ concentrations well above health-based standards. Thus, while not a substitute for on-ground monitoring, satellite remote sensing can accelerate progress in urban air quality monitoring by filling spatial gaps, informing monitor placements and estimating long-term temporal trends.

Annex 1
Air quality monitoring innovations (cont.)

Remote sensing estimates require specialized technical skills to analyze and interpret. Although training is available, (11) most cities seeking to use remote sensing estimates for initial assessment or to inform monitor placement will need to identify technical partners with this capability.

Relevant Reading for Monitoring Phase

2 3 4

Advanced surface monitoring stations

Conventional ground monitoring networks may be complemented by a limited number of advanced surface monitoring stations that provide information on additional pollutants (e.g., hazardous or toxic air pollutants like benzene) or $PM_{2.5}$ chemical composition (12). For example, the advanced monitoring stations deployed by the US $PM_{2.5}$ Chemical Speciation Monitoring Network (CSN) (13) conduct high quality PM mass and chemical speciation measurements that support quantification of emission sources' contribution to ambient air pollution (Learn more on receptor-based source apportionment in Chapter 3).

Other filter-based air monitoring instruments available for collecting filter samples for speciation include, but not limited to, Mass Aerosol Speciation Sampler (URG Corporation), Spiral Ambient Speciation Sampler (Met One Instruments), Reference Ambient Air Sampler (Thermo Anderson) (14).

In LMIC settings where resources for permanent conventional reference monitors are not available, lower cost, filter-based PM monitors [e.g., MiniVOL sampler (Airmetrics)] or passive gaseous samplers, which measure time-integrated pollutant concentrations without using pumps, can be used in time-limited campaigns to make the case for further monitoring investments. The latter have been used in both urban (15). and remote, highly polluted areas (16,17) and can be combined with lower cost filter-based PM monitors in integrated multi-pollutant sampling units. One or more of these approaches can be deployed in citywide monitoring campaigns for land-use regression studies.

Advanced surface monitoring stations, especially when co-located with ground-based AOD measurements, can provide important evaluation data for chemical transport model simulations. These outputs can help improve air quality forecasting and evaluation of air quality management options and actions. One example is the Surface Particulate Matter Network (SPARTAN), which is a network of 19 active sites worldwide that provide publicly available data on $PM_{2.5}$ mass, chemical composition, and AOD characteristics for connection with satellite remote sensing (18,19). SPARTAN monitors are co-located with sun photometers—operated as part of the AErosol RObotic NETwork (AERONET) coordinated by the National Aeronautics and Space Administration (NASA)—for AOD measurement (18,19). Combined with continuous measurement of particle light scattering with a nephelometer, these monitors can collect seven pairs of filter samples, each integrating $PM_{2.5}$ and coarse PM ($PM_{2.5}$-10) covering a nine-day period, and operate for 63 days unattended between filter cartridge replacement and other maintenance tasks. Another unique advantage of the SPARTAN network is the use of a central laboratory using advanced methods for chemical composition analysis of filter-based samples, providing capability, comparison data and quality control beyond the capability of most LMIC city governments.

Annex 1
Air quality monitoring innovations (cont.)

Advanced surface monitoring stations can also serve as nodes that are linked to conventional air quality monitoring stations within each airshed, thus providing additional information on spatial variability in pollutant concentrations at high temporal resolution and linking the network directly to satellite-based estimates.

Relevant Reading for Monitoring Phase

3 4

High spatial resolution or “hyperlocal” monitoring—identifying urban “hot spots”

As noted in chapter 2, clustered local emission sources contribute to spatial variation and hot spots within cities. The historical emphasis on temporal specificity and air pollution episode surveillance, made limited spatial coverage of fixed-site reference monitors less of a concern. But conventional monitoring networks poorly characterize the true spatial variability in pollutant concentrations within urban areas and may mask temporal variability if major location-specific sources have different temporal emission patterns. This may be relevant in rapidly developing economies where diverse arrays of numerous small sources are present and increasing emphasis on characterizing spatial variation in air pollution and associated sources is warranted (20,21).

Spatial gradients in NO2, black carbon (BC), CO and in some locations SO2 are generally more pronounced and better indicators of local emission sources than $PM_{2.5}$¬, which derives from local and upwind sources. Similarly, O3, which entirely originates in upwind NOx and VOC emissions and chemical transformation, is less spatially variable than primary pollutants. Three monitoring approaches to characterize spatial variation in pollutant levels at high (~100m) resolution are described below. Operational dispersion models are another method that requires highly space and time resolved emissions data (22), discussed in the next chapter. These lower-cost approaches for characterizing spatial variation could be useful for informing and evaluating geographically localized interventions, such as low emission zones or motor-vehicle-free zones, and for guiding the placement of more expensive fixed site monitors within an urban area.

Land use regression modeling has revolutionized understanding of air pollution variability within urban areas and become increasingly the norm for epidemiologic investigations of long-term exposure to air pollution (23). In this approach, targeted measurements are collected over defined periods at a relatively high number (~50–100) of locations within an urban area. These spatially dense air pollution measurements are used with geospatial data describing air pollution sources (e.g. road or traffic density, land use, source proximity) in a simple regression model. As the geospatial data are typically available throughout urban areas at high resolution (10–100m), models can estimate highly spatially resolved annual or seasonal air pollutant concentrations. Because the focus of such studies is understanding persistent spatial gradients they often use methods that integrate samples over a period of one to two weeks, using passive methods for gaseous pollutants, such as NO2 (24), and active samplers for filter-based measurements of PM mass, black carbon and other chemical constituents.

Land use regression approaches are typically limited in the temporal resolution of modeled estimates (often seasonal or annual); timeliness of data is limited by time needed for laboratory processing of integrated samples and data analysis.

Land use regression studies require technical capacity that is beyond that of most city governments and will most often require collaboration with academic researchers or other technical partners.

Mobile monitoring is an approach in which high quality instruments relevant to one or more pollutants of interest are deployed in one or more vehicles to collect measurements while repeated driving a planned route. Measurements are analyzed to map air quality— especially for primary pollutants with strong spatial gradients, such as NOx (NO + NO2), BC and ultrafine particles (UFP)—at high spatial resolution throughout urban areas. A recent example demonstrated automated data processing and a highly scalable approach (25) with instruments deployed in dedicated vehicles, identifying small but poorly controlled local emissions sources that may be common even in cities that have generally good ambient air quality. Mobile monitoring's greatest potential strength is its efficiency and cost effectiveness, which could be further enhanced with monitors deployed on existing commercial (e.g. Uber, taxis, delivery vehicles) or public fleets (buses, police vehicles, etc.).

In contrast, mobile monitoring may be a less efficient approach for characterizing pollutants that have more limited spatial variability (e.g, $PM_{2.5}$, ozone). In addition, most mobile monitoring datasets alone are insufficient to characterize spatial patterns of pollution at locations away from roads and temporal variation in patterns by day and week, given that a small monitoring fleet cannot be everywhere at once. Finally, because mobile monitoring can rapidly generate large amounts of spatiotemporally complex data, a successful application of this technique requires a well-trained team experienced in analyzing this unique type of data.

Low-cost sensor networks are a promising innovation with many applications, particularly when integrated with other modeling approaches. Portable, low cost devices for detecting air contaminants in real time have a long history, but in recent years advances in sensor technology and microelectronics have captured the imagination of several air quality stakeholders and innovators, including civil society organizations. The surge in interest and development has produced commercially available devices for the consumer market. (26). Low-cost sensors have been used by citizen groups when government measurement data have been unavailable or considered unreliable (for example due to spatial gaps that miss pollution hot spots).

To date, several limitations of low-cost sensors have prevented the realization of their potential. Sensor accuracy and precision has been a major issue (27). In addition, many low-cost sensors have been developed by start-up firms, creating concerns regarding their longer-term availability, data ownership and a lack of transparency about proprietary device algorithms and performance testing data for some devices. In response, a number of local, national and international agencies have initiated testing and evaluation programs for specific sensors as well as guidance regarding their deployment in networks (28–32). An additional limitation of low-cost sensors is that accuracy, precision and freedom from interference is currently limited for contaminants other than particulate matter (mass or count), carbon monoxide and VOCs.

Among the proposed applications of low-cost sensors is that of linked networks with large numbers of them, densely deployed to assess changes in pollutant concentrations over small spatial areas and short time periods (32). However, the usefulness of data collected by a large dense network of such devices is far from clear. A short spike (seconds to minutes) in levels measured by a single sensor may indicate a malfunctioning sensor or a transient increase in highly localized air pollution. The latter has little relevance for air quality management or public health unless it affects a large population or occurs regularly.

Operational considerations also pose a barrier to sustained operation of a low-cost sensor network. Air pollution data collected with inaccurate or faulty sensors or collected without a sound, well documented and designed sampling protocol and attention to operations, maintenance and QA/QC will limit its value (33). While the low cost of sensor units is appealing, personnel and other resource costs of device deployment, maintenance, calibration, and replacement along with data network management and maintenance (34) could offset much or all of the savings on instrument purchase. Additionally, the complexity and computing needs for data management, analysis and QA/QC can tax the capacity of LMIC government agencies. There is also the potential for such data collected by citizen groups to distract limited government air quality personnel and resources from efforts to control identified, important pollution sources.

As sensor quality and networking algorithms improve, there is potential for these approaches to improve our understanding of air quality, particularly where a high-quality reference monitor serves as a data node to help calibrate a larger network of low-cost sensors and where academic, government and citizen groups collaborate to design sensor deployment, data capture, analysis and interpretation. A summary of the best practices to guide such efforts has been published by the World Meteorological Organization and is available in the Annex 2 of the document (32).

As government data products improve and increasingly meet citizen goals for accessible air quality information, the demand for citizen-based sensors and networks to fill data gaps may decline, but their applications in citizen-science partnerships, engagement and awareness-raising will likely remain.

Annex 1 | Table 1
Monitoring Approaches Components and Considerations

Method	Capabilities and considerations	Spatial and temporal resolution	Equipment costs* and resources needed	Strengths	Limitations
Reference fixed-location monitor	Accurate, precise measurements suitable for comparison to regulatory standards, monitoring long-term trends, supporting forecasting and short-term health advisories.	Up to 1 per 2-4 km2 area to assess air pollution at an urban airshed scale. Daily to hourly or finer temporal resolution	• Moderate ($US 20-30K+) for $PM_{2.5}$ monitor • High ($US s100-200K) for multi-pollutant (including gaseous) site. • Additional costs for structure, land, power and personnel.	Gold-standard" measurement quality.	High cost and site requirements, including reliable power supply, limit number of sites and spatial resolution.
Monitoring Innovations					
Advanced surface particle monitor	Reference grade PM filter-based sampler for measuring mass concentration and chemical composition.	1 or 2 monitors per urban airshed. Temporal resolution can be 1-several days	• 1 or 2 monitors per urban airshed. Temporal resolution can be 1-several days • Moderate ($US 50K for SPARTAN instrument) • Low operating cost ($10K / year). • Colocation with aerosol optical depth (AOD)) instruments improves remote-sensing based measures.	High quality PM mass and particle composition for source apportionment. Cost effective for local measurement and improvement of remote sensing estimates.	Co-location with AOD instruments limits ideal locations.
Satellite remote sensing – based estimates	Estimates for any location of $PM_{2.5}$ and NO2, using satellite and surface measurements and chemical transport models.	~ 10 km2 or better. Annual-average or daily concentrations.	No cost to individual cities or other users.	Very low-cost, multi-year, global coverage, including regions with sparse official monitoring.	More uncertain in regions with sparse surface monitors. Misses some hotspots.
Land use regression models	Models use pollution measurements and spatial predictors to estimate concentrations, at high spatial resolution within urban areas.	50-300 m2 spatial resolution. Seasonal or annual average temporal resolution.	• Moderate per study cost ($US 45 - 75K). • Requires local predictor data and specialized modeling skills.	High spatial resolution, low-cost, especially useful for traffic-related air pollution.	Modeled estimates not measurements, limited by predictor datasets.
Mobile monitoring	Mobile measurement of multiple pollutants with reference quality monitors in real-time while repeatedly driving city streets.	• ~30-100m2 spatial resolution. • Annual or seasonal average temporal resolution.	• Moderate per campaign cost ($US 75K) • High initial capital cost for instruments, building vehicle measurement package.	• Multiple pollutants, high-quality instruments, fine spatial resolution • One vehicle and instruments package can map many areas.	• Pollutant measurement and mapping limited to roads. • Low temporal resolution. • High initial capital costs and technical expertise required.
Low cost sensor network	Network of multiple low-cost sensors to monitor at high spatial and temporal resolution. $PM_{2.5}$ sensor technology most mature.	Variable spatial resolution and number of sensors. Time resolution ‹ 1 minute.	• Low per sensor ($US 100-500) • Moderate ($US 30K) for data integration. • Additional personnel costs for ongoing instrument deployment, calibration and maintenance.	• Semi-quantitative insights on air quality and sources at high space-time resolution. • Can promote citizen engagement.	• Poor data quality and interferences limit data quality beyond PM sensors. • Low sensor cost may be offset limited sensor data quality and lifespan plus high personnel input costs. • Uncertain public health action value of brief, highly localized "spikes".

* Cost are estimates for illustration only. Actual costs will depend on exchange rates, tariffs and other factors.

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Annex 1 | References

1 1van Donkelaar A, Martin R, Verduzco C, Brauer M, Kahn R, Levy R, et al. A hybrid approach for predicting $PM_{2.5}$ exposure: Van donkelaar et al. respond. Environ Health Perspect. 2010;118(10).

2 Kloog I, Koutrakis P, Coull BA, Lee HJ, Schwartz J. Assessing temporally and spatially resolved PM2.5 exposures for epidemiological studies using satellite aerosol optical depth measurements. Atmos Environ. 2011 Nov 1;45(35):6267–75.

3 van Donkelaar A, Martin R V, Spurr RJD, Burnett RT. High-Resolution Satellite-Derived PM2.5 from Optimal Estimation and Geographically Weighted Regression over North America. Environ Sci Technol. 2015 Sep 1;49(17):10482–91.

4 de Hoogh K, Gulliver J, Donkelaar A van, Martin R V., Marshall JD, Bechle MJ, et al. Development of West-European PM2.5 and NO2 land use regression models incorporating satellite-derived and chemical transport modelling data. Environ Res. 2016 Nov 1;151:1–10.

5 Ma Z, Hu X, Huang L, Bi J, Liu Y. Estimating Ground-Level PM 2.5 in China Using Satellite Remote Sensing. Environ Sci Technol. 2014 Jul 13;48(13):7436–44.

6 Li T, Zhang Y, Wang J, Xu D, Yin Z, Chen H, et al. All-cause mortality risk associated with long-term exposure to ambient PM2·5 in China: a cohort study. Lancet Public Health. 2018 Oct;3(10):e470–7.

7 Health Effects Institute. State of Global Air [Internet]. State of Global Air. 2019 [cited 2019 Sep 1]. Available from: https://www.stateofglobalair.org/sites/default/files/soga-2018-report.pdf

8 8Institute for Health Metrics and Evaluation [Internet]. Institute for Health Metrics and Evaluation. [cited 2018 Oct 18]. Available from: http://www.healthdata.org/institute-health-metrics-and-evaluation

9 MAIA | Investigation [Internet]. [cited 2019 Nov 7]. Available from: https://maia.jpl.nasa.gov/investigation/

10 Martin RV, Brauer M, van Donkelaar A, Shaddick G, Narain U, Dey S. No one knows which city has the highest concentration of fine particulate matter. Atmospheric Environ X. 2019 Jun 24;100040.

11 Uz S. Applied Remote Sensing Training | ARSET [Internet]. [cited 2019 Oct 18]. Available from: /home

12 Brauer M, Guttikunda SK, K a N, Dey S, Tripathi SN, Weagle C, et al. Examination of monitoring approaches for ambient air pollution: A case study for India. Atmos Environ. 2019 Nov 1;216:116940.

13 U.S. National PM2.5 Chemical Speciation Monitoring Networks—CSN and IMPROVE: Description of networks: Journal of the Air & Waste Management Association: Vol 64, No 12 [Internet]. [cited 2019 Oct 10]. Available from: https://www.tandfonline.com/doi/full/10.1080/10962247.2014.956904

14 Solomon PA, Mitchell W, Tolocka M, Norris G, Gemmill D, Wiener R, et al. Evaluation of PM2.5 chemical speciation samplers for use in the EPA National PM2.5 Chemical Speciation Network. Office of Air Quality Planning and Standards; 2000.

15 Matte TD, Ross Z, Kheirbek I, Eisl H, Johnson S, Gorczynski JE, et al. Monitoring intraurban spatial patterns of multiple combustion air pollutants in New York City: design and implementation. J Expo Sci Environ Epidemiol. 2013;23(3):223–231.

16 Carmichael GR, Ferm M, Thongboonchoo N, Woo J-H, Chan LY, Murano K, et al. Measurements of sulfur dioxide, ozone and ammonia concentrations in Asia, Africa, and South America using passive samplers. Atmos Environ. 2003 Mar 1;37(9):1293–308.

17 Krupa SV, Legge AH. Passive sampling of ambient, gaseous air pollutants: an assessment from an ecological perspective. Environ Pollut. 2000 Jan 1;107(1):31–45.

18 Snider G, Weagle CL, Murdymootoo KK, Ring A, Ritchie Y, Stone E, et al. Variation in global chemical composition of PM<inf>2.5</inf>: emerging results from SPARTAN. Atmospheric Chem Phys. 2016;16(15).

19 Snider G, Weagle CLL, Martin RV V., van Donkelaar A, Conrad K, Cunningham D, et al. SPARTAN: a global network to evaluate and enhance satellite-based estimates of ground-level particulate matter for global health applications. Atmospheric Meas Tech. 2015 Jan 30;8(1):505–21.

20 Both AF, Balakrishnan A, Joseph B, Marshall JD. Spatiotemporal Aspects of Real-Time PM2.5: Low- and Middle-Income Neighborhoods in Bangalore, India. Environ Sci Technol. 2011 Jul 1;45(13):5629–36.

21 Zhou Z, Dionisio KL, Arku RE, Quaye A, Hughes AF, Vallarino J, et al. Household and community poverty, biomass use, and air pollution in Accra, Ghana. Proc Natl Acad Sci. 2011 Jul 5;108(27):11028–33.

22 Guttikunda SK, Nishadh KA, Jawahar P. Air pollution knowledge assessments (APnA) for 20 Indian cities. Urban Clim. 2019 Mar 1;27:124–41.

23 Hoek G, Beelen R, de Hoogh K, Vienneau D, Gulliver J, Fischer P, et al. A review of land-use regression models to assess spatial variation of outdoor air pollution. Atmos Environ. 2008;42(33):7561–78.

24 Beelen R, Hoek G, Vienneau D, Eeftens M, Dimakopoulou K, Pedeli X, et al. Development of NO2 and NOx land use regression models for estimating air pollution exposure in 36 study areas in Europe–the ESCAPE project. Atmos Environ. 2013;72:10–23.

25 Apte JS, Messier KP, Gani S, Brauer M, Kirchstetter TW, Lunden MM, et al. High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data. Environ Sci Technol. 2017 Jun 20;51(12):6999–7008.

26 Dye T. Brief History of Air Quality Sensing [Internet]. TD Environmental Services. 2017 [cited 2019 Feb 20]. Available from: http://tdenviro.com/brief-history-air-quality-sensing/

27 Zheng T, Bergin MH, Johnson KK, Tripathi SN, Shirodkar S, Landis MS, et al. Field evaluation of low-cost particulate matter sensors in high- and low-concentration environments. Atmospheric Meas Tech. 2018 Aug 22;11(8):4823–46.

28 Jiao W, Hagler G, Williams R, Sharpe R, Brown R, Garver D, et al. Community Air Sensor Network (CAIRSENSE) project: evaluation of low-cost sensor performance in a suburban environment in the southeastern United States. Atmospheric Meas Tech. 2016 Nov 1;9(11):5281–92.

29 AQ-SPEC Home Page [Internet]. [cited 2019 Mar 19]. Available from: http://www.aqmd.gov/aq-spec/home

30 US EPA O. Air Sensor Toolbox for Citizen Scientists, Researchers and Developers [Internet]. US EPA. 2016 [cited 2019 Sep 2]. Available from: https://www.epa.gov/air-sensor-toolbox

31 Air Quality Map | Cowichan Valley Regional District [Internet]. [cited 2019 Sep 2]. Available from: https://www.cvrd.bc.ca/2187/Air-Quality-Map

32 Alastair C. Lewis, Erika von Schneidemesser and Richard E. Peltier (editors. Low-cost sensors for the measurement of atmospheric composition: overview of topic and future applications [Internet]. [cited 2019 Mar 19]. Available from: http://www.wmo.int/pages/prog/arep/gaw/documents/Low_cost_sensors_18_Oct.pdf

33 Aoki P, Woodruff A, Yellapragada B, Willett W. Environmental Protection and Agency: Motivations, Capacity, and Goals in Participatory Sensing. In: Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI '17 [Internet]. Denver, Colorado, USA: ACM Press; 2017 [cited 2019 Feb 26]. p. 3138–50. Available from: http://dl.acm.org/citation.cfm?doid=3025453.3025667

34 Lewis AC, Von Schneidemesser E, Peltier R, Lung C, Jones R, Zellweger C, et al. Low-cost sensors for the measurement of atmospheric composition: overview of topic and future applications Draft copy for public review.

Annex 2
Best practices for operating networks to produce high-quality datasets according to the World Meteorological Organization

Network attributes	Research networks	Regulatory networks	Sensor networks
Established primary standard	● (green)	● (green)	● (red)
Traceability to the primary standard via direct comparison	● (green)	● (green)	● (yellow)
Best practices for measurement guidelines and SOPs	● (green)	● (green)	● (red)
Use of data quality objectives (e.g. precision, accuracy, stability, drift) for an application	● (green)	● (green)	● (yellow)
Onsite maintenance	● (green)	● (green)	● (yellow)
Implementation of the QA (e.g. calibration, validation) procedures	● (green)	● (green)	● (yellow)
Comparison among instruments/sensors in the network	● (green)	● (green)	● (red)
Independent site and instrument audits	● (green)	● (green)	● (red)
Open/transparent data processing algorithms	● (yellow)	● (yellow)	● (yellow)
Open data sharing	● (green)	● (green)	● (yellow)
Site and instrument operation log	● (green)	● (green)	● (red)
In-depth training available	● (green)	● (green)	● (red)

Source: World Meteorological Organization

● (green) Required and consistently performed
● (yellow) Common practice but not consistently occurring
● (red) Encouraged, but new techniques needed

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Annex 3
Using regional and global model forecasts

Air pollution knows no boundaries; a city's air pollution often includes significant contribution from sources outside its administrative jurisdiction. This is especially true in regions with natural sources like dust storms or wildfires, cities in close proximity to other cities, industrial areas, fossil fueled power stations or to rural areas with significant sources (e.g., burning of household solid fuels or crop waste). It is crucial for policymakers to know what portion of the ambient pollution is originating from local sources within a city's jurisdiction and from non-local sources that may require a regional action plan.

Several regional and global model forecasts can be used to quantify non-local contributions of air pollution. The following table highlights some of these model outputs.

Resource	Brief description
Whole Atmosphere Community Climate Model (WACCM) Chemistry and Aerosol Forecasts	WACCM creates global and regional forecasts for a variety of air quality and climate indicators (e.g., CO, $PM_{2.5}$, NO_x, O_3, SO_2, black carbon). Several tools for visualizing the forecast products are available. • Daily 9-day global and regional forecast • 1.9 x 2.5° resolution Website: https://www2.acom.ucar.edu/acresp/forecasts-and-near-real-time-nrt-products
Copernicus Atmosphere Monitoring Service (CAMS)	Each day, CAMS provides five-day forecasts of aerosols (e.g., dust, biomass), atmospheric pollutants (e.g., $PM_{2.5}$, PM_{10}, NO_2), greenhouse gases, stratospheric ozone, the UV-Index. • Daily 5-day global and regional (e.g., SE Asia) forecast • 0.35 x 0.35° resolution Website: https://atmosphere.copernicus.eu/global-forecast-plots
Navy Aerosol Analysis and Prediction System (NAAPS) Global Aerosol model	NAAPS is a global three-dimensional aerosol and air pollution model, based primarily on the Danish Eulerian Hemispheric Model. It combines the current and expected satellite data streams with other available data and the global aerosol simulation and prediction, and provides forecasts of dust, smoke, salt, sulfate and SO_2 • Daily 6-day global and regional (e.g., SE Asia) forecast • 1 x 1° grid, at 6-hour intervals Website: https://www.nrlmry.navy.mil/aerosol/
Global Earth Observing System – Composition Forecast (GEOS-CF)	GEOS-CF system combines the GEOS weather analysis and forecasting system to provide detailed chemical analysis of a wide range of air pollutants including O_3, CO_2, NO, and $PM_{2.5}$. • Daily 5-day global and regional/country (e.g., Indonesia) forecast • 0.25 x 0.25° resolution Website: https://fluid.nccs.nasa.gov/cf/ (visualization); https://portal.nccs.nasa.gov/datashare/gmao/geos-cf (data access)
System for Integrated mod-eling of Atmospheric com-position (SILAM)	SILAM chemical transport model, developed in Finnish Meteorological Institutes, provides air quality forecasts of concentrations, total column loads, and depositions of air pollutants (e.g., SO_2, NO, NO_2, O_3, $PM_{2.5}$, PM_{10}) • Daily 4-day forecast over global and Europe, Northern Europe, and South-East Asia • 1.44° resolution Website: http://silam.fmi.fi
Spectral Radiation-Transport Model for Aerosol Species (SPRINTARS)	SPRINTARS is a numerical model that has been developed for simulating effects on the climate system and condition of atmospheric pollution by atmospheric aerosols ($PM_{2.5}$ and soil dust) on the global scale. • Daily 7-day forecast over global, East Asia and Asia • 35km horizontal resolution Website: https://sprintars.riam.kyushu-u.ac.jp/forecast.html
The European Monitoring and Evaluation Program Unified Model for the UK (EMEP4UK)	The EMEP4UK is an off-line atmospheric chemistry transport model that simulates hourly to annual average atmospheric composition and deposition of various pollutants (e.g., PM_{10}, $PM_{2.5}$, SO_2, O_3). Dry and wet deposition of pollutants are routinely calculated by the model. • Daily 3-day forecast over global, European Union and United Kingdom • 100 km to 1 km horizontal resolution Website: http://www.emep4uk.ceh.ac.uk/emepglobalforecast

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References

1 GBD Compare | IHME Viz Hub [Internet]. [cited 2018 Jun 27]. Available from: http://vizhub.healthdata.org/gbd-compare

2 World Health Organization. Global Urban Ambient Air Pollution Database (update 2016) [Internet]. WHO. 2016 [cited 2016 Oct 21]. Available from: http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/

3 WHO | Air quality guidelines - global update 2005 [Internet]. WHO. [cited 2016 Sep 14]. Available from: http://www.who.int/phe/health_topics/outdoorair/outdoorair_aqg/en/

4 United Nations Environment Program (UNEP). Actions on Air Quality: Policies & Programmes for imporving Air Quality Around the World [Internet]. 2015 [cited 2019 Sep 10]. Available from: https://wedocs.unep.org/bitstream/handle/20.500.11822/17203/AQ_GlobalReport_Summary.pdf?sequence=1&isAllowed=y

5 Chow JC, Watson JG, Feldman HJ, Nolen JE, Wallerstein B, Hidy GM, et al. Will the Circle Be Unbroken: A History of the U.S. National Ambient Air Quality Standards. J Air Waste Manag Assoc. 2007 Oct;57(10):1151–63.

6 Longhurst JWS, Barnes JH, Chatterton TJ, Hayes ET, Williams WB. Progress with air quality management in the 60 years since the UK clean Air Act, 1956. Lessons, failures, challenges and opportunities. Int J Sustain Dev Plan. 2016 Aug 31;11(4):491–9.

7 Marais EA, Wiedinmyer C. Air Quality Impact of Diffuse and Inefficient Combustion Emissions in Africa (DICE-Africa). Environ Sci Technol. 2016 Oct 4;50(19):10739–45.

8 GBD MAPS Working Group. Burden of Disease Attributable to Major Air Pollution Sources in India [Internet]. [cited 2018 Jan 10]. Available from: https://www.healtheffects.org/system/files/GBD-MAPS-SpecRep21-India.pdf

9 Chafe ZA, Brauer M, Klimont Z, Van Dingenen R, Mehta S, Rao S, et al. Household Cooking with Solid Fuels Contributes to Ambient $PM_{2.5}$ Air Pollution and the Burden of Disease. Environ Health Perspect. 2014 Dec;122(12):1314–20.

10 Reddington CL, Yoshioka M, Balasubramanian R, Ridley D, Toh YY, Arnold SR, et al. Contribution of vegetation and peat fires to particulate air pollution in Southeast Asia. Environ Res Lett. 2014;9(9):094006.

11 Publication: World Energy Outlook Special Report 2016: Energy and Air Pollution [Internet]. [cited 2016 Sep 15]. Available from: http://www.iea.org/publications/freepublications/publication/weo-2016-special-report-energy-and-air-pollution.html

12 Burden of Disease Attributable to Coal-Burning and Other Air Pollution Sources in China [Internet]. Health Effects Institute. 2016 [cited 2016 Aug 18]. Available from: https://www.healtheffects.org/publication/burden-disease-attributable-coal-burning-and-other-air-pollution-sources-china

13 Burnett RT, Pope CA III, Ezzati M, Olives C, Lim SS, Mehta S, et al. An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure. Environ Health Perspect [Internet]. 2014 Feb 11 [cited 2018 Jan 16]; Available from: http://ehp.niehs.nih.gov/1307049/

14 Burnett R, Chen H, Szyszkowicz M, Fann N, Hubbell B, Pope CA, et al. Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. Proc Natl Acad Sci. 2018 Sep 18;115(38):9592–7.

15 Global Warming of 1.5 oC — [Internet]. [cited 2019 Jan 28]. Available from: https://www.ipcc.ch/sr15/

16 Scovronick N, Dora C, Fletcher E, Haines A, Shindell D. Reduce short-lived climate pollutants for multiple benefits. The Lancet. 2015 Nov 7;386(10006):e28–31.

17 Zhang Y, Loh C, Louie PKK, Liu H, Lau AKH. The roles of scientific research and stakeholder engagement for evidence-based policy formulation on shipping emissions control in Hong Kong. J Environ Manage. 2018 Oct 1;223:49–56.

18 Bachmann J. Will the Circle Be Unbroken: A History of the U.S. National Ambient Air Quality Standards. J Air Waste Manag Assoc. 2007 Jun;57(6):652–97.

19 Guidance Document: National Planning for reducing short-lived climate pollutants (SNAP) | Climate & Clean Air Coalition [Internet]. [cited 2017 Jun 28]. Available from: http://www.ccacoalition.org/en/resources/guidance-document-national-planning-reducing-short-lived-climate-pollutants-snap

20 Air quality in europe 2017 [Internet]. European Environment Agency. [cited 2018 Apr 3]. Available from: https://www.eea.europa.eu/publications/air-quality-in-europe-2017

21 Crippa M, Janssens-Maenhout G, Dentener F, Guizzardi D, Sindelarova K, Muntean M, et al. Forty years of improvements in European air quality: regional policy-industry interactions with global impacts. Atmos Chem Phys. 2016 Mar 22;16(6):3825–41.

22 Guerreiro CBB, Foltescu V, de Leeuw F. Air quality status and trends in Europe. Atmos Environ. 2014 Dec 1;98:376–84.

23 US EPA O. The Clean Air Act and the Economy [Internet]. 2016 [cited 2016 Nov 25]. Available from: https://www.epa.gov/clean-air-act-overview/clean-air-act-and-economy

24 Matthias V, Arndt JA, Aulinger A, Bieser J, Gon HD van der, Kranenburg R, et al. Modeling emissions for three-dimensional atmospheric chemistry transport models. J Air Waste Manag Assoc. 2018 Aug 3;68(8):763–800.

25 Kadaverugu R, Sharma A, Matli C, Biniwale R. High Resolution Urban Air Quality Modeling by Coupling CFD and Mesoscale Models: a Review. Asia-Pac J Atmospheric Sci [Internet]. 2019 Feb 28 [cited 2019 May 21]; Available from: https://doi.org/10.1007/s13143-019-00110-3

26 Guttikunda SK, Nishadh KA, Jawahar P. Air pollution knowledge assessments (APnA) for 20 Indian cities. Urban Clim. 2019 Mar 1;27:124–41.

27 Clean Air Plans [Internet]. [cited 2019 May 28]. Available from: http://www.aqmd.gov/home/air-quality/clean-air-plans

28 LADCO [Internet]. [cited 2019 Oct 9]. Available from: https://www.ladco.org/

29 OTC Home Page - Ozone Transport Commission - OTCAir.org [Internet]. [cited 2019 Oct 9]. Available from: https://otcair.org/

30 US EPA O. Cross-State Air Pollution Rule (CSAPR) [Internet]. US EPA. 2016 [cited 2019 Oct 9]. Available from: https://www.epa.gov/csapr

31 Clancy L, Goodman P, Sinclair H, Dockery DW. Effect of air-pollution control on death rates in Dublin, Ireland: an intervention study. Lancet Lond Engl. 2002 Oct 19;360(9341):1210–4.

32 Kheirbek I, Haney J, Douglas S, Ito K, Caputo Jr S, Matte T. The public health benefits of reducing fine particulate matter through conversion to cleaner heating fuels in New York City. Environ Sci Technol. 2014;48(23):13573–13582.

33 Holman C, Harrison R, Querol X. Review of the efficacy of low emission zones to improve urban air quality in European cities. Atmos Environ. 2015 Jun 1;111:161–9.

34 Bachmann J. Managing Air Quality: Lessons from the American Experience. :14.

35 Integrated Programme for Better Air Quality in Asia [Internet]. Clean Air Asia. 2015 [cited 2019 Sep 1]. Available from: http://cleanairasia.org/ibaq-programme/

36 Pinder RW, Klopp JM, Kleiman G, Hagler GSW, Awe Y, Terry S. Opportunities and challenges for filling the air quality data gap in low- and middle-income countries. Atmos Environ. 2019 Oct 15;215:116794.

37 Cohen AJ, Brauer M, Burnett R, Anderson HR, Frostad J, Estep K, et al. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. The Lancet [Internet]. 2017 Apr 10 [cited 2017 Apr 12];0(0). Available from: http://thelancet.com/journals/lancet/article/PIIS0140-6736(17)30505-6/abstract

38 Backes CH, Nelin T, Gorr MW, Wold LE. Early life exposure to air pollution: how bad is it? Toxicol Lett. 2013 Jan 10;216(1):47–53.

39 Barakat-Haddad C, Elliott SJ, Pengelly D. Health Impacts of Air Pollution: A Life Course Approach for Examining Predictors of Respiratory Health in Adulthood. Ann Epidemiol. 2012 Apr 1;22(4):239–49.

40 Achakulwisut P, Brauer M, Hystad P, Anenberg SC. Global, national, and urban burdens of paediatric asthma incidence attributable to ambient NO2 pollution: estimates from global datasets. Lancet Planet Health [Internet]. 2019 Apr 10 [cited 2019 Apr 15];0(0). Available from: https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(19)30046-4/abstract

41 Héroux M-E, Anderson HR, Atkinson R, Brunekreef B, Cohen A, Forastiere F, et al. Quantifying the health impacts of ambient air pollutants: recommendations of a WHO/Europe project. Int J Public Health. 2015 Jul 1;60(5):619–27.

42 Di Q, Wang Y, Zanobetti A, Wang Y, Koutrakis P, Choirat C, et al. Air Pollution and Mortality in the Medicare Population. N Engl J Med. 2017 Jun 29;376(26):2513–22.

43 Beelen R, Raaschou-Nielsen O, Stafoggia M, Andersen ZJ, Weinmayr G, Hoffmann B, et al. Effects of long-term exposure to air pollution on natural-cause mortality: an analysis of 22 European cohorts within the multicentre ESCAPE project. The Lancet. 2014 Mar;383(9919):785–95.

44 WHO | Air quality guidelines - global update 2005 [Internet]. WHO. [cited 2019 Jan 11]. Available from: http://www.who.int/airpollution/publications/aqg2005/en/

45 Künzli N, Medina S, Kaiser R, Quénel P, Horak F, Studnicka M. Assessment of deaths attributable to air pollution: should we use risk estimates based on time series or on cohort studies? Am J Epidemiol. 2001 Jun 1;153(11):1050–5.

46 Lall R, Kendall M, Ito K, Thurston GD. Estimation of historical annual $PM_{2.5}$ exposures for health effects assessment. Atmos Environ. 2004 Oct 1;38(31):5217–26.

47 AAP_database_methods_2014.pdf [Internet]. [cited 2019 Feb 13]. Available from: https://www.who.int/airpollution/data/AAP_database_methods_2014.pdf

48 Li L, Wu AH, Cheng I, Chen J-C, Wu J. Spatiotemporal estimation of historical $PM_{2.5}$ concentrations using PM_{10}, meteorological variables, and spatial effect. Atmos Environ. 2017 Oct 1;166:182–91.

49 Martin RV, Brauer M, van Donkelaar A, Shaddick G, Narain U, Dey S. No one knows which city has the highest concentration of fine particulate matter. Atmospheric Environ X. 2019 Jun 24;100040.

50 Xu L, Batterman S, Chen F, Li J, Zhong X, Feng Y, et al. Spatiotemporal characteristics of $PM_{2.5}$ and PM10 at urban and corresponding background sites in 23 cities in China. Sci Total Environ. 2017 Dec 1;599–600:2074–84.

51 Pinto JP, Lefohn AS, Shadwick DS. Spatial Variability of $PM_{2.5}$ in Urban Areas in the United States. J Air Waste Manag Assoc. 2004 Apr 1;54(4):440–9.

52 Brauer M, Guttikunda SK, K a N, Dey S, Tripathi SN, Weagle C, et al. Examination of monitoring approaches for ambient air pollution: A case study for India. Atmos Environ. 2019 Nov 1;216:116940.

53 van Donkelaar A, Martin R, Verduzco C, Brauer M, Kahn R, Levy R, et al. A hybrid approach for predicting $pm_{2.5}$ exposure: Van donkelaar et al. respond. Environ Health Perspect. 2010;118(10).

54 Health Effects Institute. State of Global Air [Internet]. State of Global Air. 2019 [cited 2019 Sep 1]. Available from: https://www.stateofglobalair.org/sites/default/files/soga-2018-report.pdf

55 Institute for Health Metrics and Evaluation [Internet]. Institute for Health Metrics and Evaluation. [cited 2018 Oct 18]. Available from: http://www.healthdata.org/institute-health-metrics-and-evaluation

56 Anenberg SC, Achakulwisut P, Brauer M, Moran D, Apte JS, Henze DK. Particulate matter-attributable mortality and relationships with carbon dioxide in 250 urban areas worldwide. Sci Rep. 2019 Aug 9;9(1):1–6.

57 U.S. National $PM_{2.5}$ Chemical Speciation Monitoring Networks—CSN and IMPROVE: Description of networks: Journal of the Air & Waste Management Association: Vol 64, No 12 [Internet]. [cited 2019 Oct 10]. Available from: https://www.tandfonline.com/doi/full/10.1080/10962247.2014.956904

58 Snider G, Weagle CL, Murdymootoo KK, Ring A, Ritchie Y, Stone E, et al. Variation in global chemical composition of PM‹inf›$_{2.5}$‹/inf›: emerging results from SPARTAN. Atmospheric Chem Phys. 2016;16(15).

59 Snider G, Weagle CLL, Martin RV V., van Donkelaar A, Conrad K, Cunningham D, et al. SPARTAN: a global network to evaluate and enhance satellite-based estimates of ground-level particulate matter for global health applications. Atmospheric Meas Tech. 2015 Jan 30;8(1):505–21.

60 Both AF, Balakrishnan A, Joseph B, Marshall JD. Spatiotemporal Aspects of Real-Time $PM_{2.5}$: Low- and Middle-Income Neighborhoods in Bangalore, India. Environ Sci Technol. 2011 Jul 1;45(13):5629–36.

61 Zhou Z, Dionisio KL, Arku RE, Quaye A, Hughes AF, Vallarino J, et al. Household and community poverty, biomass use, and air pollution in Accra, Ghana. Proc Natl Acad Sci. 2011 Jul 5;108(27):11028–33.

62 Hoek G, Beelen R, de Hoogh K, Vienneau D, Gulliver J, Fischer P, et al. A review of land-use regression models to assess spatial variation of outdoor air pollution. Atmos Environ. 2008;42(33):7561–78.

63 Dye T. Brief History of Air Quality Sensing [Internet]. TD Environmental Services. 2017 [cited 2019 Feb 20]. Available from: http://tdenviro.com/brief-history-air-quality-sensing/

64 Alastair C. Lewis, Erika von Schneidemesser and Richard E. Peltier (editors. Low-cost sensors for the measurement of atmospheric composition: overview of topic and future applications [Internet]. [cited 2019 Mar 19]. Available from: http://www.wmo.int/pages/prog/arep/gaw/documents/Low_cost_sensors_18_Oct.pdf

65 Aoki P, Woodruff A, Yellapragada B, Willett W. Environmental Protection and Agency: Motivations, Capacity, and Goals in Participatory Sensing. In: Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI '17 [Internet]. Denver, Colorado, USA: ACM Press; 2017 [cited 2019 Feb 26]. p. 3138–50. Available from: http://dl.acm.org/citation.cfm?doid=3025453.3025667

66 Lewis AC, Von Schneidemesser E, Peltier R, Lung C, Jones R, Zellweger C, et al. Low-cost sensors for the measurement of atmospheric composition: overview of topic and future applications Draft copy for public review.

67 Zheng T, Bergin MH, Johnson KK, Tripathi SN, Shirodkar S, Landis MS, et al. Field evaluation of low-cost particulate matter sensors in high- and low-concentration environments. Atmospheric Meas Tech. 2018 Aug 22;11(8):4823–46.

68 Jiao W, Hagler G, Williams R, Sharpe R, Brown R, Garver D, et al. Community Air Sensor Network (CAIRSENSE) project: evaluation of low-cost sensor performance in a suburban environment in the southeastern United States. Atmospheric Meas Tech. 2016 Nov 1;9(11):5281–92.

69 AQ-SPEC Home Page [Internet]. [cited 2019 Mar 19]. Available from: http://www.aqmd.gov/aq-spec/home

70 US EPA O. Air Sensor Toolbox for Citizen Scientists, Researchers and Developers [Internet]. US EPA. 2016 [cited 2019 Sep 2]. Available from: https://www.epa.gov/air-sensor-toolbox

71 Air Quality Map | Cowichan Valley Regional District [Internet]. [cited 2019 Sep 2]. Available from: https://www.cvrd.bc.ca/2187/Air-Quality-Map

72 GHG Protocol for Cities | Greenhouse Gas Protocol [Internet]. [cited 2019 Oct 24]. Available from: https://ghgprotocol.org/greenhouse-gas-protocol-accounting-reporting-standard-cities

73 LMIC Urban Air Pollution Solutions [Internet]. [cited 2019 Oct 23]. Available from: https://breathelife2030.org/wp-content/uploads/2019/08/USAID_APSolutionsDoc_070219.pdf

74 Home - CAMx [Internet]. [cited 2019 Oct 24]. Available from: http://www.camx.com/

75 Heaps C, Kuylenstierna JCI, Hicks K, Vallack H, Malley C. The Long-range Energy Alternatives Planning Integrated Benefits Calculator (LEAP-IBC). 2017 Nov 30 [cited 2019 Oct 24]; Available from: https://www.sei.org/publications/leap-ibc/

76 FASST - European Commission [Internet]. [cited 2019 Oct 24]. Available from: http://tm5-fasst.jrc.ec.europa.eu/

77 urbanemissions.info [Internet]. [cited 2018 Oct 18]. Available from: http://www.urbanemissions.info/

78 Crippa M, Guizzardi D, Muntean M, Schaaf E, Dentener F, van Aardenne JA, et al. Gridded emissions of air pollutants for the period 1970–2012 within EDGAR v4.3.2. Earth Syst Sci Data. 2018 Oct 26;10(4):1987–2013.

79 Marais EA, Wiedinmyer C. Air Quality Impact of Diffuse and Inefficient Combustion Emissions in Africa (DICE-Africa). Environ Sci Technol. 2016 Oct 4;50(19):10739–45.

80 Multi-resolution Emission Inventory for China [Internet]. [cited 2019 Oct 23]. Available from: http://www.meicmodel.org/

81 US EPA O. AP-42: Compilation of Air Emissions Factors [Internet]. US EPA. 2016 [cited 2019 May 1]. Available from: https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors

82 EMEP/EEA air pollutant emission inventory guidebook [Internet]. European Environment Agency. [cited 2019 Nov 4]. Available from: https://www.eea.europa.eu/themes/air/emep-eea-air-pollutant-emission-inventory-guidebook/emep

83 Guttikunda DS. Urban Particulate Pollution Source Apportionment. :16.

84 US EPA O. SPECIATE [Internet]. US EPA. 2015 [cited 2019 Oct 24]. Available from: https://www.epa.gov/air-emissions-modeling/speciate

A

85 WHO | Database on source apportionment studies for particulate matter in the air (PM10 and $PM_{2.5}$) [Internet]. WHO. [cited 2019 Oct 24]. Available from: http://www.who.int/quantifying_ehimpacts/global/source_apport/en/

86 Murukutla N, Negi NS, Puri P, Mullin S, Onyon L. Online media coverage of air pollution risks and current policies in India: A content analysis. WHO South-East Asia J Public Health. 2017 Jul 1;6(2):41.

87 Wirtz BW, Piehler R, Thomas M-J, Daiser P. Resistance of Public Personnel to Open Government: A cognitive theory view of implementation barriers towards open government data. Public Manag Rev. 2016 Oct 20;18(9):1335–64.

88 Huang R, Lai T, Zhou L. Proposing a framework of barriers to opening government data in China: A critical literature review. Libr Hi Tech Bradf. 2017;35(3):421–38.

89 SIATA,EAFIT, SIATA. SIATA - Sistema de Alerta Temprana del valle de Aburrá [Internet]. [cited 2019 Sep 2]. Available from: https://siata.gov.co/siata_nuevo/

90 AirNow [Internet]. [cited 2019 Sep 2]. Available from: https://airnow.gov/

91 CCR [Internet]. [cited 2019 Oct 29]. Available from: https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing

92 London Air Quality Network - King's College London [Internet]. [cited 2019 Feb 26]. Available from: https://www.londonair.org.uk/LondonAir/Default.aspx

93 New York City Community Air Survey (NYCCAS) [Internet]. [cited 2019 Mar 20]. Available from: https://commonercenter.org/nyccas.html

94 Data C of NY NYC Open. NYC Open Data [Internet]. [cited 2019 Sep 2]. Available from: http://nycod-wpengine.com/

95 Environment & Health Data Portal [Internet]. [cited 2019 Sep 2]. Available from: http://a816-dohbesp.nyc.gov/IndicatorPublic/Subtopic.aspx?theme_code=1,4&subtopic_id=122

96 OpenAQ [Internet]. [cited 2019 Sep 2]. Available from: https://openaq.org/#/?_k=wyvih5

97 USC training launches a new era of air pollution health research in eastern Africa – Eastern Africa GEOHealth Hub [Internet]. [cited 2019 Mar 20]. Available from: https://geohealthhub.org/2016/06/30/usc-training-launches-a-new-era-of-air-pollution-health-research-in-eastern-africa/

98 Simon Ng; Chubin Lin; Jimmy Chan. Tender Reference AS 08-068: Study on Marine Vessels Emission Inventory Final Report [Internet]. 2012. Available from: https://www.epd.gov.hk/epd/sites/default/files/epd/english/environmentinhk/air/studyrpts/files/EPD_MVEIS_Final_Report_v7_approved_120528.pdf

99 Hazy Perceptions - A new report on air pollution [Internet]. Vital Strategies. [cited 2019 Sep 2]. Available from: https://www.vitalstrategies.org/resources/hazy-perceptions-a-new-report-on-air-pollution/

100 Moses E. Fighting for Clean Air Around the Globe. Conf Proc. :19.

101 UNEP Air Pollution Country Actions Information [Internet]. 2016 [cited 2016 Oct 31]. Available from: http://www.unep.org/Transport/airquality/

102 Abdoun A. Fuel Quality and Emission Standard Developments in Africa. :23.

103 World Population Review. Accra Population 2019 (Demographics, Maps, Graphs) [Internet]. [cited 2019 Jul 24]. Available from: http://worldpopulationreview.com/world-cities/accra-population/

104 Jorge Ubaldo Colin Pescina. The Economic Base of Accra, Ghana - Advanced Issue in Development Planning. 2013.

105 State of Global Air. Explore the Data [Internet]. [cited 2019 Sep 5]. Available from: https://www.stateofglobalair.org/data/#/air/plot

106 HEI Household Air Pollution–Ghana Working Group. Contribution of Household Air Pollution to Ambient Air Pollution in Ghana: Using Available Evidence to Prioritize Future Action. Communication 19. Boston, MA; 2019.

107 Zhou Z, Dionisio KL, Verissimo TG, Kerr AS, Coull B, Howie S, et al. Chemical characterization and source apportionment of household fine particulate matter in rural, peri-urban, and urban West Africa. Environ Sci Technol. 2014;48(2):1343–51.

108 Guttikunda SK. Urban Emissions [Internet]. 2019. Available from: www.urbanemissions%0A.info/

109 The ASEAN Secretariat. ASEAN Statistical Yearbook 2018. Jakarta; 2018.

110 Workd Population Review. Bangkok Population 2019 (Demographics, Maps, Graphs) [Internet]. [cited 2019 Jul 24]. Available from: http://worldpopulationreview.com/world-cities/bangkok-population/

111 Arunmas P. Businesses downbeat on prospects [Internet]. Bangkok Post. 2016 [cited 2019 Jul 24]. Available from: https://www.bangkokpost.com/business/995133/businesses-downbeat-on-prospects

112 Office of the National Economic and Social Development Board, Office of the Prime Minister. The Twelfth National Economic and Social Development plan (2017-2021). 2017.

113 Chongpoonphol T. Source of PM and Health Impacts in Bangkok.

114 Chestnut LG, Ostro BD, Vichit-Vadakan N, Laixuthai A, Smith KR, Tsai FC, et al. Executive summary health effects of particulate matter air pollution in bangkok. 1998.

115 Arphorn S, Ishimaru T, Hara K, Mahasandana S. Considering the effects of ambient particulate matter on the lung function of motorcycle taxi drivers in Bangkok, Thailand. J Air Waste Manag Assoc. 2018 Feb 1;68(2):139–45.

116 Pollution Control Department, Ministry of Natural Resources and Environment. Thailand State of Pollution Report 2003. Bangkok, Thailand; 2003.

117 Chuersuwan N, Nimrat S, Lekphet S, Kerdkumrai T. Levels and major sources of $PM_{2.5}$ and PM10 in Bangkok Metropolitan Region. Environ Int. 2008;34(5):671–7.

118 UN Habitat. Case Study: Bangkok's strategy to tackle air pollution. In: State of the World's Cities 2008/2009. 2008.

119 Perera R. Promoting travel demand reduction in transport sector in cities of Asian developing countries: Case of Bangkok. In: Workshop paper, Urban Environmental Management (UEM), SERD, Asian Institute of Technology. 2006.

120 Beijing Municipal Bureau of Statistics, NBS Survey Office in Beijing. Beijing Statistical Yearbook - Annual Data [Internet]. 2018 [cited 2019 May 10]. Available from: http://tjj.beijing.gov.cn/English/AD/

121 China Briefing. Beijing City Profile - Industry, Economics, and Policy [Internet]. 2019 [cited 2019 May 10]. Available from: https://www.china-briefing.com/news/beijing-industry-economics-policy/

122 National Bureau of Statistics of China. National Data [Internet]. 2019 [cited 2019 May 10]. Available from: http://data.stats.gov.cn/english/

123 GBD MAPS Working Group. Special Report 20: Burden of Disease Attributable to Coal-Burning and Other Major Sources of Air Pollution in China. Health Effects Institute. 2016.

124 The United States Department of State. AirNow [Internet]. [cited 2019 Jan 8]. Available from: https://airnow.gov/index.cfm?action=airnow.global_summary

125 Liu J, Kiesewetter G, Klimont Z, Cofala J, Heyes C, Schöpp W, et al. Mitigation pathways of air pollution from residential emissions in the Beijing-Tianjin-Hebei region in China. Environ Int. 2019;236–44.

126 Li X, Zhang Q, Zhang Y, Zheng B, Wang K, Chen Y, et al. Source contributions of urban $PM_{2.5}$ in the Beijing-Tianjin-Hebei region: Changes between 2006 and 2013 and relative impacts of emissions and meteorology. Atmos Environ. 2015;123:229–39.

127 National Development and Reform Commission. Clean winter heating plan for Northern China (2017-2021). 2017.

128 Wang L, Zhang F, Pilot E, Yu J, Nie C, Holdaway J, et al. Taking action on air pollution control in the Beijing-Tianjin-Hebei (BTH) region: Progress, challenges and opportunities. Int J Environ Res Public Health. 2018;15(2).

129 Ministry of Environment. Action Plan for Comprehensive Control of Air pollution in Autumn and Winter 2019-2020 in Beijing, Tianjin, Hebei and surrounding areas. 2019.

130 Barrington-Leigh C, Baumgartner J, Carter E, Robinson BE, Tao S, Zhang Y. An evaluation of air quality, home heating and well-being under Beijing's programme to eliminate household coal use. Nat Energy. 2019;4(5):416–23.

131 UNESCAP. Battambang, Cambodia - City Overview. 2018.

132 World Population Review. Population of Cities in Cambodia [Internet]. 2019. Available from: http://worldpopulationreview.com/countries/cambodia-population/cities/

133 UNEP IGES. Participatory waste management approach for climate change mitigation - the case of Battambang city. 2018.

134 Sothea K. Status of Air Quality Management in Phnom Penh City, Cambodia. In: Launch Meeting on Cambodia And Laos Initiative for

Building Human Resources for the Environment (CALIBRE) Project. 2008.
135 Cogut A. Open Burning of Waste: A Global Health Disaster. R20 Regions of Climate Change. 2016.
136 Climate and Clean Air Coalition. Battambang, Cambodia [Internet]. Municipal solid waste knowledge platform. Available from: https://www.waste.ccacoalition.org/participant/battambang-cambodia
137 Hong Kong Department of Health. Health Facts of Hong Kong. 2018.
138 Chen EKY. Foreign trade and economic growth in Hong Kong: experience and prospects. Trade Struct Change Pac Asia. 1987;333–78.
139 To WM, Lee PKC. Energy consumption and economic development in Hong Kong, China. Energies. 2017;10(11):1–13.
140 Census and Statistics Department. The Four Key Industries and Other Selected Industries - Concepts and Methods [Internet]. 2005 [cited 2018 Nov 20]. Available from: https://www.censtatd.gov.hk/hkstat/sub/sc80.jsp
141 Marine department. The Port - fact sheet. 2018.
142 Hong Kong Marine Department. Port Benchmarking for Assessing Hong Kong's Maritime Services and Associated Costs with other Major International Ports. 2006.
143 Hong Kong Marine Department. Time Series Statistics - Vessel Arrivals by Ocean/River and Cargo/Passenger Vessels. 2018.
144 Hong Kong Marine Department. Ranking of Container Ports of the World. 2018.
145 GHK. Study on Hong Kong Port Cargo Forecasts 2005/2006 Executive Summary. 2008.
146 Gall C, Rafelghem M Van, Exchange C. Marine Emission Reduction Options for Hong Kong and the Pearl River Delta Region. Hong Kong; 2006.
147 Natural Resources Defense Council. Prevention and Control of Shipping and Port Air Emissions in China. 2014.
148 Environmental Bureau. A Clean Air Plan for Hong Kong. 2013.
149 Corbett JJ, Winebrake JJ, Green EH, Kasibhatla P, Eyring V, Lauer A. Mortality from ship emissions: a global assessment. Environ Sci Technol. 2007 Dec 15;41(24):8512–8.
150 Liu H, Fu M, Jin X, Shang Y, Shindell D, Faluvegi G, et al. Health and climate impacts of ocean-going vessels in East Asia. Nat Clim Change. 2016;6(November):6–11.
151 Lau K, Wu WM, Fung JCH, Henry RC, Barron B. Significant Marine Source for SO2 levels in Hong Kong. Analysis. 2005.
152 Lau AK, Yu J, Wong T-W, Yu TI, Poore MW. Assessment of Toxic Air Pollutant Measurements in Hong Kong. 2003.
153 Ng SKW, Loh C, Lin C, Booth V, Chan JWM, Yip ACK, et al. Policy change driven by an AIS-assisted marine emission inventory in Hong Kong and the Pearl River Delta. Atmos Environ. 2013;76:102–12.
154 Ng SKW, Lin C, Chan J, Yip ACK, Lau AKH, Fung JCH. Study on Marine Vessels Emission Inventory. 2012.
155 Ng S. Fair Winds Charter: How Civic Exchange Influenced Policymaking to Reduce Ship Emissions in Hong Kong 2006-2015. Hong Kong; 2018.
156 Li Y, Lau A, Wong A, Fung J. Decomposition of the wind and nonwind effectson observed year-to-year air quality variation. J Geophys Res Atmospheres. 2014;119:6207–20.
157 Legislative Council of The Hong Kong Special Adminstrative Region of The People's Republic of China. Cap 311Y - Air Pollution Control (Marine Light Diesel) Regulation. Hong kong; 2014.
158 Legislative Council of The Hong Kong Special Adminstrative Region of The People's Republic of China. Air Pollution Control (Ocean Going Vessels) (Fuel at Berth) Regulation. 2015;
159 Hong Kong Environmental Protection Department. Air [Internet]. Hong Kong Environmental Protection Department. 2016 [cited 2016 May 16]. Available from: http://www.epd.gov.hk/epd/english/environmentinhk/air/air_maincontent.html
160 Hong Kong Environment Bureau. Clean air plan for Hong Kong: 2013-2017 Progress Report. 2017.
161 Legislative Council of The Hong Kong Special Adminstrative Region. Cap 311 AB - Air Pollution Control (Fuel for Vessels) Regulation [Internet]. 2019. Available from: https://www.elegislation.gov.hk/hk/cap311AB
162 Ishtiaque A, Shrestha M, Chhetri N, Ishtiaque A, Shrestha M, Chhetri N. Rapid Urban Growth in the Kathmandu Valley, Nepal: Monitoring Land Use Land Cover Dynamics of a Himalayan City with Landsat Imageries. Environments. 2017 Oct 8;4(4):72.
163 Shivit Bakrania. Urbanisation and urban growth in Nepal (GSDRC Helpdesk Research Report 1294). Birmingham, UK:; 2015.
164 Ministry of Population and Environment. National Population Report 2017. 2017.
165 Nepal Rastra Bank Research Department. Survey Report on the Share of Kathmandu Valley in the National Economy. 2012.
166 World Bank. Nepal - Country Environmental Analysis : Strengthening Institutions and Management Systems for Enhanced Environmental Governance. Washington, DC; 2007 Dec.
167 MinErgy Nepal, International Centre for Integrated Mountain Development, Climate and Clean Air Coalition. Brick Sector in Nepal: National Policy Framework. 2017.
168 Joshi SK, Dudani I. Environmental health effects of brick kilns in Kathmandu valley. Kathmandu Univ Med J KUMJ. 6(1):3–11.
169 Baum E. Present Status of Brick Production in Asia. In: Proceedings of the Workshop on public policies to mitigate environmental impact of artesanal brick production. 2012.
170 Maskey U, Sanu M, Dangol B. Study on Evaluating Energy Conservation Potential of Brick Production in SAARC Countries - A Report on Nepal. Islamabad, Pakistan; 2013.
171 Kim BM, Park J-S, Kim S-W, Kim H, Jeon H, Cho C, et al. Source apportionment of PM 10 mass and particulate carbon in the Kathmandu Valley, Nepal. Atmos Environ. 2015;123:190–9.
172 Climate & Clean Air Coalition. CCAC Annual Report 2015-2016.
173 Benfield A. 2015 Nepal Earthquake Event Recap Report. 2015.
174 ICIMOD. Building back better brick kilns in Nepal. 2016.
175 Nepal S, Mahapatra PS, Adhikari S, Shrestha S, Sharma P, Shrestha KL, et al. A comparative study of stack emissions from straight-line and zigzag brick kilns in Nepal. Atmosphere. 2019;10(3).
176 International Centre for Integrated Mountain development, Climate and Clean Air Coalition, Greentech Knowledge Solution, MinErgy. Design Manual - Improved Fixed Chimney Brick Kiln. 2015.
177 The Hindu. Nepal leads the way in cutting emissions in brick kilns [Internet]. 2018 [cited 2019 May 13]. Available from: https://www.thehindu.com/sci-tech/energy-and-environment/nepal-leads-the-way-in-cutting-emissions-in-brick-kilns/article24039609.ece
178 Pradhan BB. Case Study of the Brick Kiln Experience - Solutions to Reduce Air Pollution in South Asia. In: Better Air Quality Conference. Kuching, Malaysia; 2018.
179 City of New York. NYC Population: Current and Projected Populations [Internet]. [cited 2019 May 8]. Available from: https://www1.nyc.gov/site/planning/data-maps/nyc-population/current-future-populations.page
180 NYC Planning. Employment Patterns in New York City - Trends in a growing economy. 2016.
181 New York City Department of Health and Mental Hygiene. The New York City Community Air Survey - Results from Winter Monitoring 2008-2009. 2008.
182 New York City Department of Health and Mental Hygiene. Air Pollution and the Health of New Yorkers: The Impact of Fine Particles and Ozone. 2011.
183 City of New York. PlaNYC - a greener, greater New York. 2007.
184 Matte TD, Ross Z, Kheirbek I, Eisl H, Johnson S, Gorczynski JE, et al. Monitoring intraurban spatial patterns of multiple combustion air pollutants in New York City: Design and implementation. J Expo Sci Environ Epidemiol. 2013 May 16;23(3):223–31.
185 Clougherty JE, Kheirbek I, Eisl HM, Ross Z, Pezeshki G, Gorczynski JE, et al. Intra-urban spatial variability in wintertime street-level concentrations of multiple combustion-related air pollutants: The New York City Community Air Survey (NYCCAS). J Expo Sci Environ Epidemiol. 2013 May 30;23(3):232–40.
186 Clougherty Iyad Kheirbek Sarah Johnson Grant Pezeshki J Bryan Jacobsen Daniel Kass Thomas Matte JE, Strickland CH, Kizzy Charles-Guzman J, Eisl John E Gorczynski Alyssa Benson Andres Camacho Jordan Werbe-Fuentes Jonah Haviland-Markowitz Rolando Munoz Anna Tilles Steven Markowitz Zev Ross Spatial Analysis Zev Ross HM. The New York City Community Air Survey Supplemental Report - Nickel Concentrations in Ambient Fine Particles: Winter Monitoring Background and Methods. 2008.
187 Iyad Kheirbek, Sarah Johnson, Kazuhiko Ito, Thomas Matte, Daniel Kass, Steven A Caputo, et al. New York City Trends in Air Pollution and its Health Consequences. 2013.
188 Kheirbek I, Haney J, Douglas S, Ito K, Caputo S, Matte T. The Public Health Benefits of Reducing Fine Particulate

Matter through Conversion to Cleaner Heating Fuels in New York City. Environ Sci Technol. 2014 Dec 2;48(23):13573–82.
189 Kheirbek I, Johnson S, Ross Z, Pezeshki G, Ito K, Eisl H, et al. Spatial variability in levels of benzene, formaldehyde, and total benzene, toluene, ethylbenzene and xylenes in New York City: a land-use regression study. Environ Health. 2012 Dec 31;11(1):51.
190 Kheirbek I, Ito K, Neitzel R, Kim J, Johnson S, Ross Z, et al. Spatial Variation in Environmental Noise and Air Pollution in New York City. J Urban Health. 2014 Jun 1;91(3):415–31.
191 Kheirbek I, Haney J, Douglas S, Ito K, Matte T. The contribution of motor vehicle emissions to ambient fine particulate matter public health impacts in New York City: a health burden assessment. Environ Health. 2016 Dec 26;15(1):89.
192 Weinberger KR, Kinney PL, Robinson GS, Sheehan D, Kheirbek I, Matte TD, et al. Levels and determinants of tree pollen in New York City. J Expo Sci Environ Epidemiol. 2016 Dec 21;28(2):119.
193 California Department of Finance. E-1 Population Estimates for Cities, Counties, and the State — January 1, 2018 and 2019 [Internet]. [cited 2019 May 9]. Available from: http://www.dof.ca.gov/Forecasting/Demographics/Estimates/E-1/
194 Port of Oakland. History of Port of Oakland [Internet]. [cited 2019 May 9]. Available from: https://www.portofoakland.com/port/history/
195 City of Oakland. Economic & Workforce Development [Internet]. [cited 2019 May 9]. Available from: https://www.oaklandca.gov/departments/economic-and-workforce-development
196 U.S. Census Bureau. American FactFinder - Community Facts [Internet]. [cited 2019 May 9]. Available from: https://factfinder.census.gov/faces/nav/jsf/pages/community_facts.xhtml?src=bkmk
197 Apte JS, Messier KP, Gani S, Brauer M, Kirchstetter TW, Lunden MM, et al. High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data. Environ Sci Technol. 2017;51(12):6999–7008.
198 J.D. M, E. N, M. B. Within-urban variability in ambient air pollution: Comparison of estimation methods. Atmos Environ. 2008;42(5):1359–69.
199 Apte JS. Mapping air pollution with Google Street View cars. Austin, TX; 2019.
200 Alexeeff SE, Roy A, Shan J, Liu X, Messier K, Apte JS, et al. High-resolution mapping of traffic related air pollution with Google street view cars and incidence of cardiovascular events within neighborhoods in Oakland, CA. Environ Health Glob Access Sci Source. 2018;17(1).
201 Oakland Planning and Building Department. Downtown Oakland Disparity Analysis. City of Oakland; 2018.
202 Oakland P of. Revised Draft Seaport Air Quality 2020 and Beyond Plan. 2018.
203 Air Quality Management District. California AB 617 Background [Internet]. [cited 2019 May 22]. Available from: http://www.airquality.org/air-quality-health/community-air-protection/ab-617-background
204 Kloog I, Koutrakis P, Coull BA, Lee HJ, Schwartz J. Assessing temporally and spatially resolved $PM_{2.5}$ exposures for epidemiological studies using satellite aerosol optical depth measurements. Atmos Environ. 2011 Nov 1;45(35):6267–75.
205 van Donkelaar A, Martin R V, Spurr RJD, Burnett RT. High-Resolution Satellite-Derived $PM_{2.5}$ from Optimal Estimation and Geographically Weighted Regression over North America. Environ Sci Technol. 2015 Sep 1;49(17):10482–91.
206 de Hoogh K, Gulliver J, Donkelaar A van, Martin R V., Marshall JD, Bechle MJ, et al. Development of West-European $PM_{2.5}$ and NO2 land use regression models incorporating satellite-derived and chemical transport modelling data. Environ Res. 2016 Nov 1;151:1–10.
207 Ma Z, Hu X, Huang L, Bi J, Liu Y. Estimating Ground-Level $PM_{2.5}$ in China Using Satellite Remote Sensing. Environ Sci Technol. 2014 Jul 13;48(13):7436–44.
208 Li T, Zhang Y, Wang J, Xu D, Yin Z, Chen H, et al. All-cause mortality risk associated with long-term exposure to ambient PM2·5 in China: a cohort study. Lancet Public Health. 2018 Oct;3(10):e470–7.
209 MAIA | Investigation [Internet]. [cited 2019 Nov 7]. Available from: https://maia.jpl.nasa.gov/investigation/
210 Uz S. Applied Remote Sensing Training | ARSET [Internet]. [cited 2019 Oct 18]. Available from: /home
211 Solomon PA, Mitchell W, Tolocka M, Norris G, Gemmill D, Wiener R, et al. Evaluation of $PM_{2.5}$ chemical speciation samplers for use in the EPA National $PM_{2.5}$ Chemical Speciation Network. Office of Air Quality Planning and Standards; 2000.
212 Matte TD, Ross Z, Kheirbek I, Eisl H, Johnson S, Gorczynski JE, et al. Monitoring intraurban spatial patterns of multiple combustion air pollutants in New York City: design and implementation. J Expo Sci Environ Epidemiol. 2013;23(3):223–231.
213 Carmichael GR, Ferm M, Thongboonchoo N, Woo J-H, Chan LY, Murano K, et al. Measurements of sulfur dioxide, ozone and ammonia concentrations in Asia, Africa, and South America using passive samplers. Atmos Environ. 2003 Mar 1;37(9):1293–308.
214 Krupa SV, Legge AH. Passive sampling of ambient, gaseous air pollutants: an assessment from an ecological perspective. Environ Pollut. 2000 Jan 1;107(1):31–45.
215 Beelen R, Hoek G, Vienneau D, Eeftens M, Dimakopoulou K, Pedeli X, et al. Development of NO2 and NOx land use regression models for estimating air pollution exposure in 36 study areas in Europe–the ESCAPE project. Atmos Environ. 2013;72:10–23.
216 Apte JS, Messier KP, Gani S, Brauer M, Kirchstetter TW, Lunden MM, et al. High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data. Environ Sci Technol. 2017 Jun 20;51(12):6999–7008.
217 Global Atmosphere Watch Programme (GAW) | World Metereological Organization [Internet]. [cited 2020 Jan 13]. Available from: https://community.wmo.int/activity-areas/gaw

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