INNOVATION AND ACTION GUIDE

Accelerating City Progress on Clean Air

Vital Strategies

Bloomberg Philanthropies

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Acknowledgements

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The authors and contributors to this guide are grateful to government and non-government stakeholders and partners in Addis Ababa, Ethiopia and Jakarta, Indonesia who provided invaluable feedback and insight during consultations held in 2019. During those interactions, the planning framework presented here was used to guide discussions about each city's air quality management capacity and planning. The feedback received was used to inform the content of this guide, considering their challenges and opportunities. In addition, we benefitted from the perspectives of several of the contributors and external reviewers, whose input was informed by years of experience consulting with government and non-government partners on air pollution assessment and policy in low- and middle-income countries.

This publication was made possible with financial support from Bloomberg Philanthropies.

Revised: February 25, 2020

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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.

This document—*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

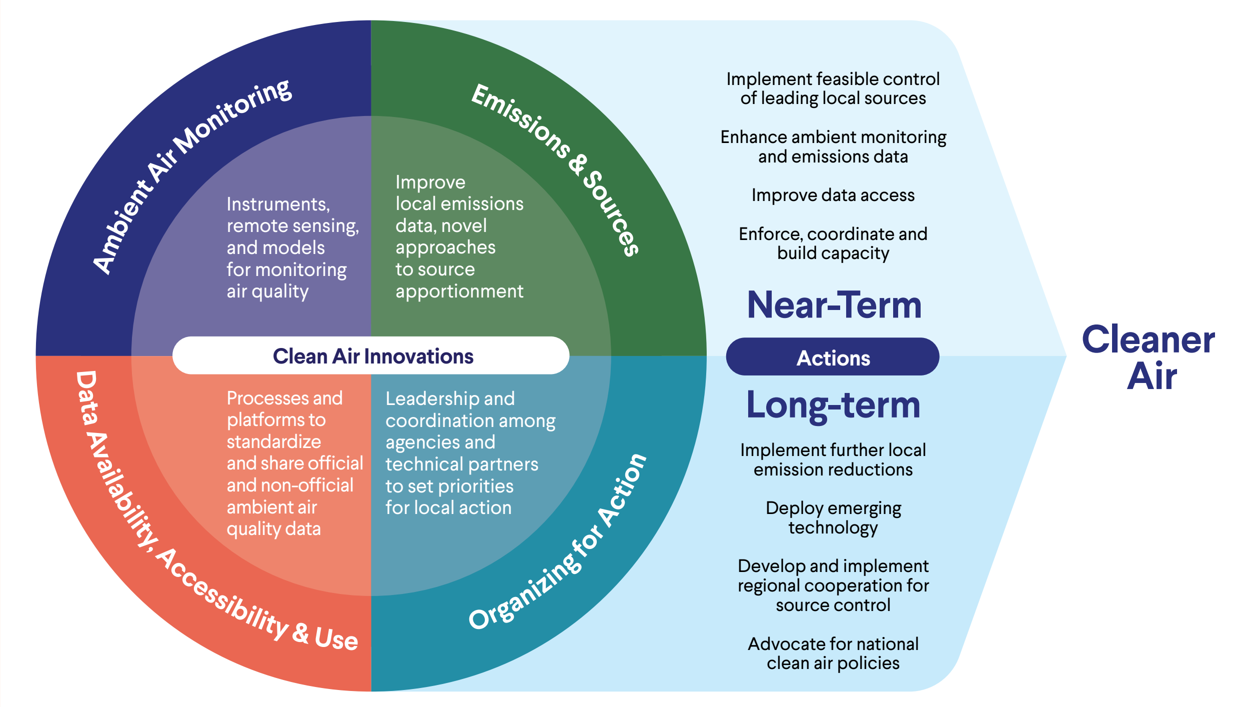
The guide lays out a new approach to accelerate clean air progress in cities within low- and middle-income countries. It recognizes air pollution as a massive public health crisis with unique, but solvable challenges faced by urban areas in low- and middle-income countries with limited air quality management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



- Eight 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 chapter 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.

Assessing Emissions and Sources
This chapter provides guidance for applying different emissions and source assessment data and approaches in phases tailored to a city's baseline capacity. Thorough understanding of emissions and sources contributing to air pollution in a city is central to identifying appropriate control measures for the local context.

Objectives by local capacity phase:
Phase 1: Identify, assess, and use available data and tools

Phase 2: Establish an official emissions tracking and source assessment process, and develop procedures for data use
Phase 3: Sustain routine collection, improvement and use of emissions and source data
Phase 4: Build advanced, highly space- and time-resolved emissions, source and forecasting capability

Innovative application of both source-based and receptor-based approaches to characterize leading sources of pollution allows assessors to identify consistencies and discrepancies in the data and provides a strong foundation for strategic clean air interventions. As technical capacity and data availability grows, all cities can apply innovations and refine data to inform sustained improvements in air quality.

Data Availability, Accessibility, and Use
This chapter describes the role of open, accessible data in building support for clean air action, promoting utilization by technical and non-technical users, and informing clean air policy. A phased approach to the creation and application of open and accessible data is also explored here.

Objectives by local capacity phase:
Phase 1: Government commitment to collecting and sharing official air quality data
Phase 2: Routine communication, increased access and developing interoperability of relevant air quality data
Phase 3: Expanded access, integration and communication of air quality data
Phase 4: Developing an advanced, integrated air quality data system

Innovative solutions to common technical, social, political, and financial barriers to a publicly accessible air quality data system are presented in this chapter along with examples of successful data sharing platforms that cities may use as a model. Through building an advanced, open air quality ecosystem, all cities can maximize the utility of reliable data for both official and nonofficial end users.

Organization for Action
This chapter explores the role and requirements of government executive leadership in coordinating the development and implementation of effective air quality management. The achievement of four critical goals are central to building and sustaining government commitment:

1. Identify and champion political leadership;
2. Secure and sustain political commitment;
3. Assess technical capacity within government agencies and build capacity with partnerships; and
4. Build and engage a public constituency for ongoing clean air action.

Innovative partnerships among government entities, technical experts, civil society, the private sector, and others are central to accelerating clean air action in all cities, especially those in low- and middle-income settings. Moreover, translating the technical tools described in this guide into effective, rapid, and sustained progress requires political leadership and a government commitment to advance the right to clean air as well as effective and sustained organization, partnerships, planning and implementation.

1

Accelerating urban clean air progress in low- and middle-income countries

1.1 The Problem: Air pollution is the deadliest global environmental health risk

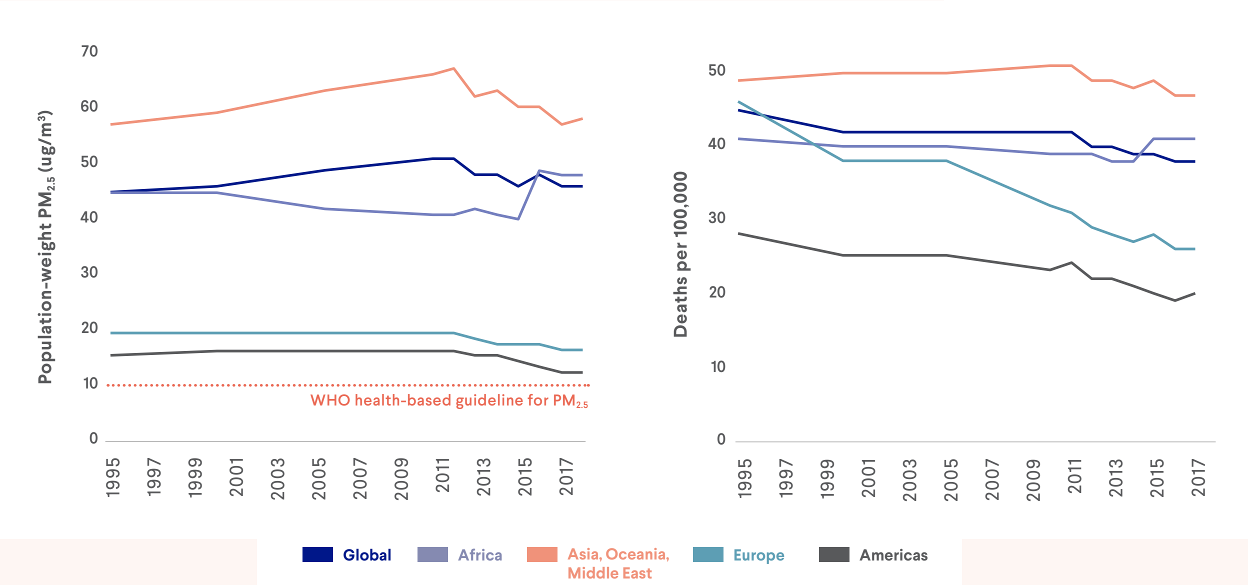
Air pollution is the fifth leading mortality risk factor globally, causing nearly 5 million annual deaths, most from exposure to fine particles ($PM_{2.5}$)[a] in outdoor and indoor air. (1) More than 90% of the world's population lives where air quality does not meet health-based guidelines (2).

In the most polluted regions of Asia and Africa, outdoor annual average $PM_{2.5}$ concentrations are several times above health-based standards (3) and pollution levels and deaths from air pollution are rising or not decreasing (Figure 1a & Figure 1b). In low- and middle-income countries, rapid economic development, urbanization and proliferation of emissions from industry, electric power generation and motorized transport in countries with limited or no air quality regulation (4) have caused steep increases in harmful pollution (Figure 1c). During the 20th century in many higher-income countries, these same sources grew and were eventually controlled (5,6) by modern air quality management practices. Compounding the air pollution challenge in many low- and middle-income countries is the persistence of pre-industrial pollution sources such as inefficient burning of crop waste, solid fuels used in households, forests for land clearing and trash in open fires (7–10).

a $PM_{2.5}$ refers to airborne particles less than 2.5 microns in size, which penetrate deep into the lungs

Figure 1a & 1b

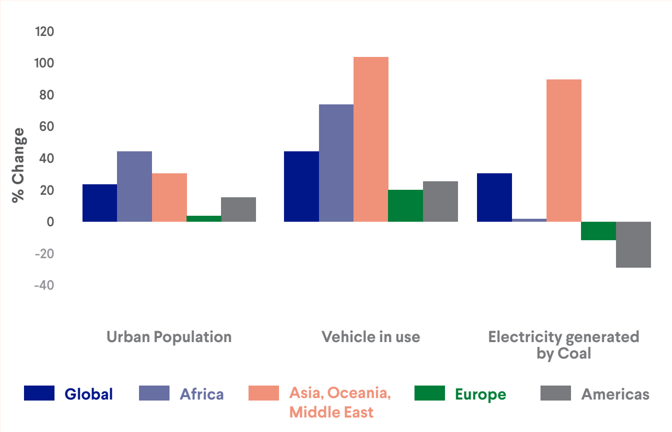
Average annual ambient $PM_{2.5}$ & age-standardized annual mortality rates attributable ambient $PM_{2.5}$, by region, 1995-2017



Ambient $PM_{2.5}$ concentrations are population-weighted estimates from remote sensing-based models that combine data from ground air pollution monitoring stations, satellite observations, and global chemical transport models. Mortality attributable to $PM_{2.5}$ is estimated from ambient $PM_{2.5}$ concentrations, cause-specific mortality rates, and estimates of exposure-mortality relationships based on global peer-reviewed studies. Source: State of Global Air, available at https://www.stateofglobalair.org

Figure 1c

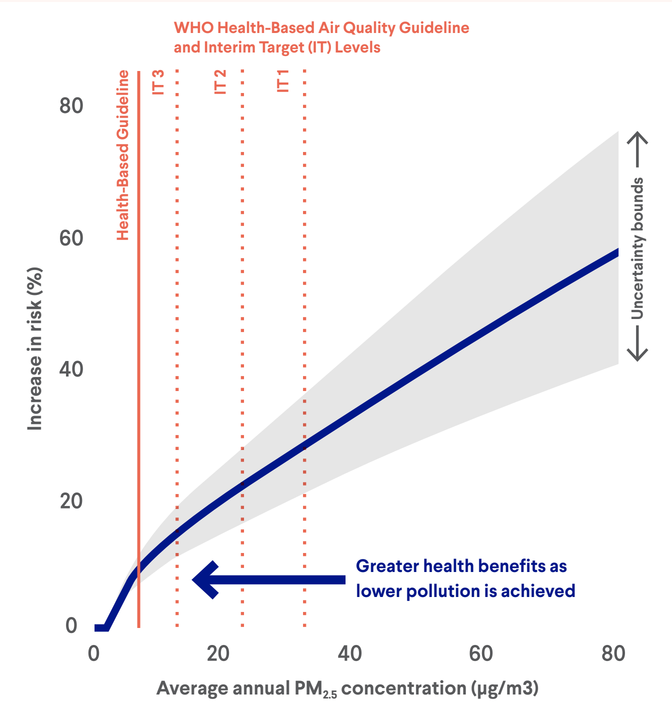
Percent change in urban population, vehicles in use and coal-fired power generation, 2005-2018



Sources: 2018 Revision of World Urbanization Prospects, available at https://population.un.org/wup/; Organisation Internationale des Constructeurs d'Automobiles (OICA) Vehicles In Use, available at http://www.oica.net/category/vehicles-in-use/; International Energy Agency (IEA) Statistics on Electricity Generation By Fuel, available at https://www.iea.org/.

Figure 1d

Percent increase in risk of mortality from noncommunicable diseases or lower respiratory tract infection related to annual average $PM_{2.5}$ concentration



Risk function based on data from 41 cohort studies in 16 countries, assuming minimum risk (0% increase at annual average $PM_{2.5}$ concentration of 2.4 µg/m3, the lowest observed concentration across all studies), charted for age 60-64 for illustration. For comparison, the World Health Organization's health-based guidance level of $PM_{2.5}$ 10 µg/m3 annual average and interim target values of 15, 25 and 35 µg/m3. The shape of the risk function is similar for other age groups and implies a global burden of mortality from ambient $PM_{2.5}$ exposure of 8.9 million, nearly twice as large as estimated for the Global Burden of Disease. Source: Adapted from Burnett, 2018 (14).

Growing and aging global populations and rising prevalence of noncommunicable disease are increasing the population with health conditions that increase susceptibility to serious illness and death from air pollution, even when pollution levels remain constant or slowly improve (8,11,12). The risk of death from air pollution increases continuously at levels of $PM_{2.5}$ above the lowest observed urban concentrations even at concentrations below World Health Organization (WHO) Air Quality Guidelines (i.e., 10 micrograms per cubic meter (µg/m³))(13,14). Therefore, all substantial air quality improvements bring sizable health benefits (Figure 1d). The global public health burden from air pollution has been extensively documented in publications and online web platforms (refer to **Annex 1**).

The global air pollution crisis is closely linked to rapidly accelerating climate change, which will continue without rapid and aggressive action to reduce climate-forcing pollutant emissions (e.g. of greenhouse gases such as CO_2) (15). Climate pollutants and air pollutants harmful to local populations have many of the same sources, solutions and regulatory frameworks, and controlling them requires the same types of expertise and capacity. In addition, two short-lived climate pollutants—black carbon (a component of $PM_{2.5}$) and methane—also contribute directly to poor local air quality.

Actions are urgently needed to combat these linked threats, but global clean air and climate action has been uneven, slow and not fully informed by knowledge of what works. More coherent, coordinated and effective climate change mitigation actions are possible with strong linkages of clean air (5,16–19) and climate policies, technical capacity and civil society mobilization.

b Climate forcing pollutants can contribute to both warming and cooling of the earth's climate (https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf]. In general, measures to reduce inefficient fuel combustion will reduce air pollutants harmful to people and the pollutants like CO² and black carbon that contribute to warming. A notable exception is the use of scrubbers to remove sulfur oxide emissions and sulfate particles but not CO² produced from coal combustion.

1.2
The Opportunity:
Proven solutions plus innovations can accelerate progress

Decades of progress in high-income countries have shown that government action can reduce air pollution even as economies and populations grow (20–23). These clean air successes were enabled by a wealth of scientific research, conventional and innovative technologies, and effective policy solutions that can be applied by governments today to reverse worsening air pollution and accelerate global clean air progress (Table 1e). This includes knowledge of the health effects of air pollution, biologic mechanisms, and exposure-response relationships for major pollutants. In addition, approaches for air pollution monitoring, exposure assessment, emissions estimation and atmospheric modeling have been developed, refined, evaluated and substantially reduced in cost (24–26). Finally, investments by wealthy countries to scale 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.

Table 1e

Proven solutions for major sectors

Major Sources	Proven, scalable solutions	Regional gaps and opportunities examples	Benefit examples
Household solid fuel combustion for cooking and heating	Expanding access, affordability and use of clean household fuels (e.g. LPG) and technologies (e.g. electric induction cookstoves)	**Household solid fuel use remains common in:** • Sub-Saharan Africa (› ¾ of households) • South, Southeast and East Asia (› 30% of households)	• China: Beijing-Tianjin-Hebei region, expanded implementation of clean fuel plan by 2030 could reduce household + outdoor air pollution deaths by 1/3 • India: Universal CHE access and use has potential to reduce national average $PM_{2.5}$ to India standard
Industry and electric power	Transboundary pollution control conventions and rules, mandated emission reductions and use of best available emission control technology, plus cap and trade or other market mechanisms . Cleaner energy sources (e.g. natural gas, wind, solar, hydro replacing coal), more efficient energy use.	**Industry and electric power generation are major sources in:** • China: more than 1/3 of ambient $PM_{2.5}$ in 2013 • Southeast Asia: under construction and planned coal-fired power plants could cause $PM_{2.5}$, SO_2 and NOx emissions to increase 2.5-3 fold by 2030	• Europe: SO_2, particulate sulfate, NO_2 and $PM_{2.5}$ reductions of 92%, 65%, 40% and 31%, respectively • United States: Cumulatively SO_2 reduced by more than 85% compared to 1995 levels and NOx by more than 80% compared to 1990 levels and ambient particulate sulfate concentration reduced ›70% from 1989-91 to 2014-16.
Vehicle emissions	Vehicle emission, fuel economy and fuel quality standards	• Europe: nearly 4 in 5 deaths from traffic-related air pollution were due to excess NO_x emissions from diesel engines. • Asia and Africa: vehicle fleets grew › 80 % from 2005-15. Many countries lack world-class emission and fuel standards.	• United States: Cumulatively 99% reduction in emissions of PM, NO_x, CO and hydrocarbon compared to 1970 vehicles. • California: 1993-2011 - 54% less NO_x emissions. Increased children's lung function growth and decreased symptoms.

Sources shown are not exhaustive but illustrative of sources that have been dramatically reduced with proven, regulatory or market approaches, scalable technologies or fuel changes. Sources: Air pollution trend in the EMEP region between 1990 and 2012, available at http://unece.org. History of the Air District, available at http://www.baaqmd.gov. Timeline of Major Accomplishments in Transportation, Air Pollution, and Climate Change, available at https://www.epa.gov/.

c Urban airsheds are metropolitan areas and other contiguous, highly urbanized geographic areas where weather, topography and economic and policy linkages of major emission sectors contribute to causes and potential solutions of poor air quality.

The formal air quality management (AQM) approaches applied in North America and Europe in the second half of the 20th century focused on setting national ambient air quality standards. Progress toward achieving these standards required actions aligned across geographic levels by state, regional, urban airshed[c] and city organizations, addressing both local pollution sources and those that come from other areas. (18, 27, 28, 29, 30) A range of pollution control strategies have been used, including: performance standards for sources like vehicles; emissions cap and trade and other market mechanisms; banning the most polluting building fuels; and, more recently, low emission zones for vehicles (17, 18, 31-33). The technical capacity needed to implement the formal national AQM efforts used in high-income countries is beyond what is currently available in many low- and middle-income countries and cities within them. Because of that, one AQM approach in particular, requiring "best available control technology," (BACT) has been recognized as a pragmatic way for low- and middle-income countries to speed near-term progress (34). BACT standards for major sources can be enacted quickly while capacity is built for an eventual comprehensive air quality management system that relies on intensive monitoring, modeling and strategy development to attain ambient air quality standards.

Thus, rapid and sustained urban clean air progress involves city, regional and national governments playing complementary roles, using multiple strategies, and combining feasible, scalable near-term actions with longer-term plans and data improvement. Cities can act to control local emissions while shaping and contributing to regional and national clean air policies.

1.3
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.

1.4
Overview of this guide

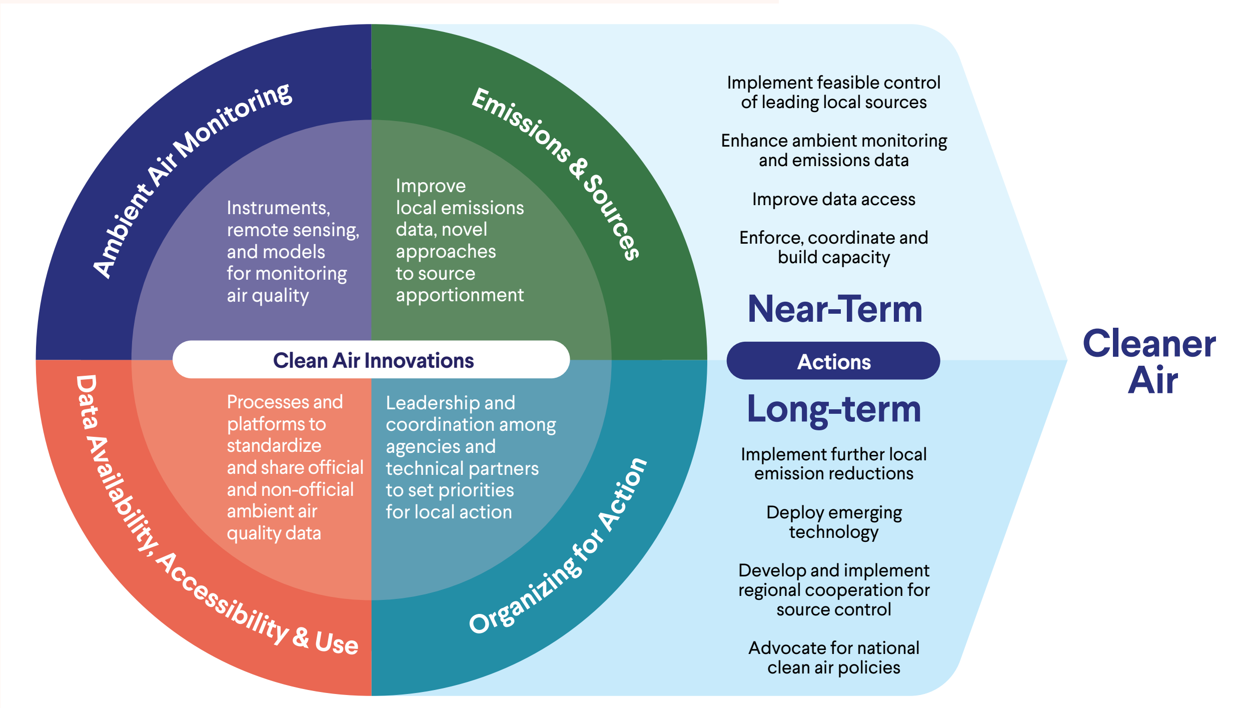
This guide covers four aspects of clean air action: air quality monitoring; assessing emissions and sources; data accessibility and use; and government organization for action, and aims to answer practical questions about each topic (Figure 1f).

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.

1

1.4 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 Pollution."

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?

2

Ambient Air Quality Monitoring

2.1 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 2a below. For a given phase, numbered icons through the chapter point to the most relevant chapter content.

Table 2a
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

2.2
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 (refer to Figure 1d).

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.

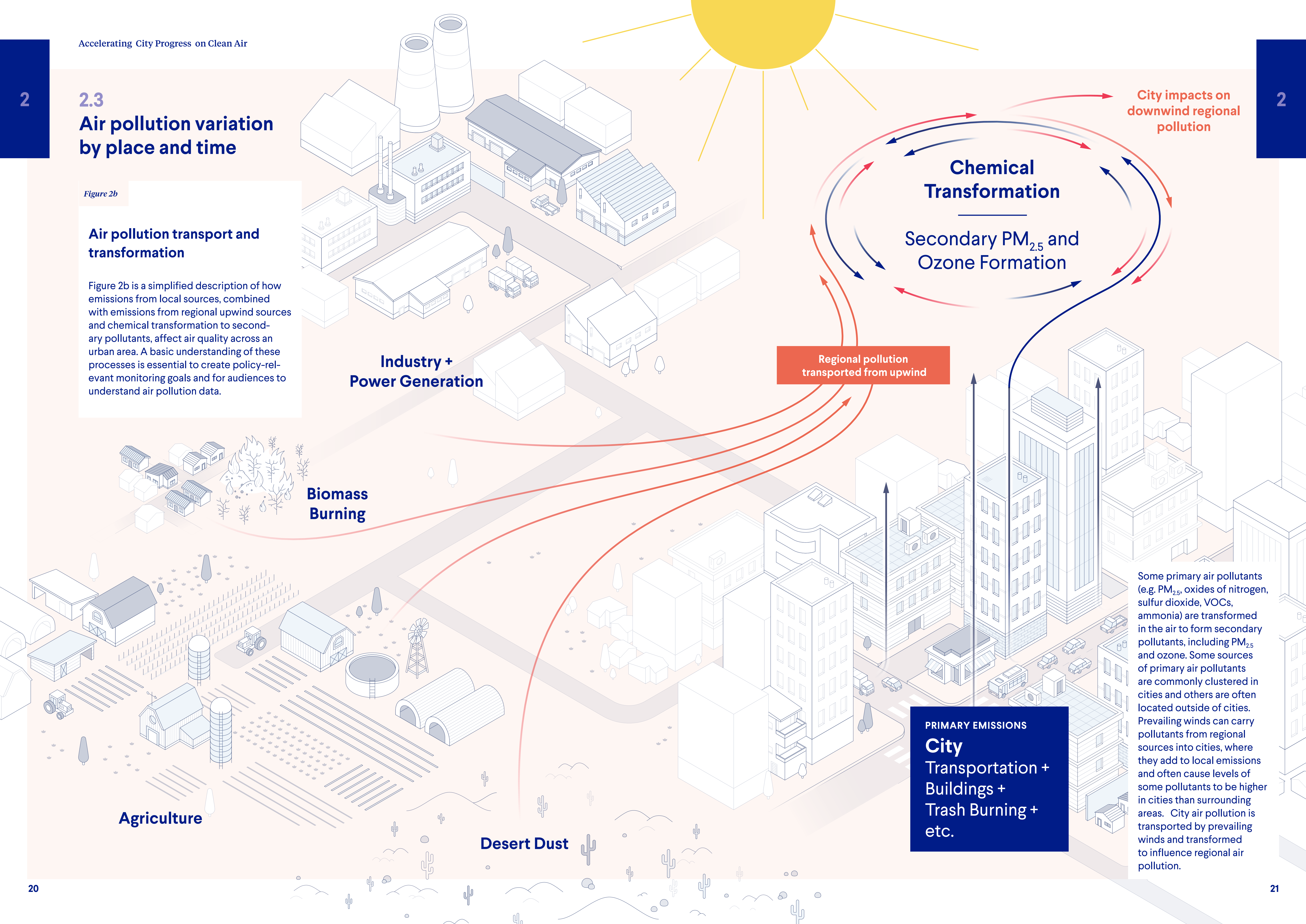
a $PM_{2.5}$ has been shown to be harmful to health; additionally, its concentration also is useful as an indicator of harmful ambient air pollution mixtures of many types of particles and gases harmful to health.

2.3
Air pollution variation by place and time

Figure 2b

Air pollution transport and transformation

Figure 2b 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.

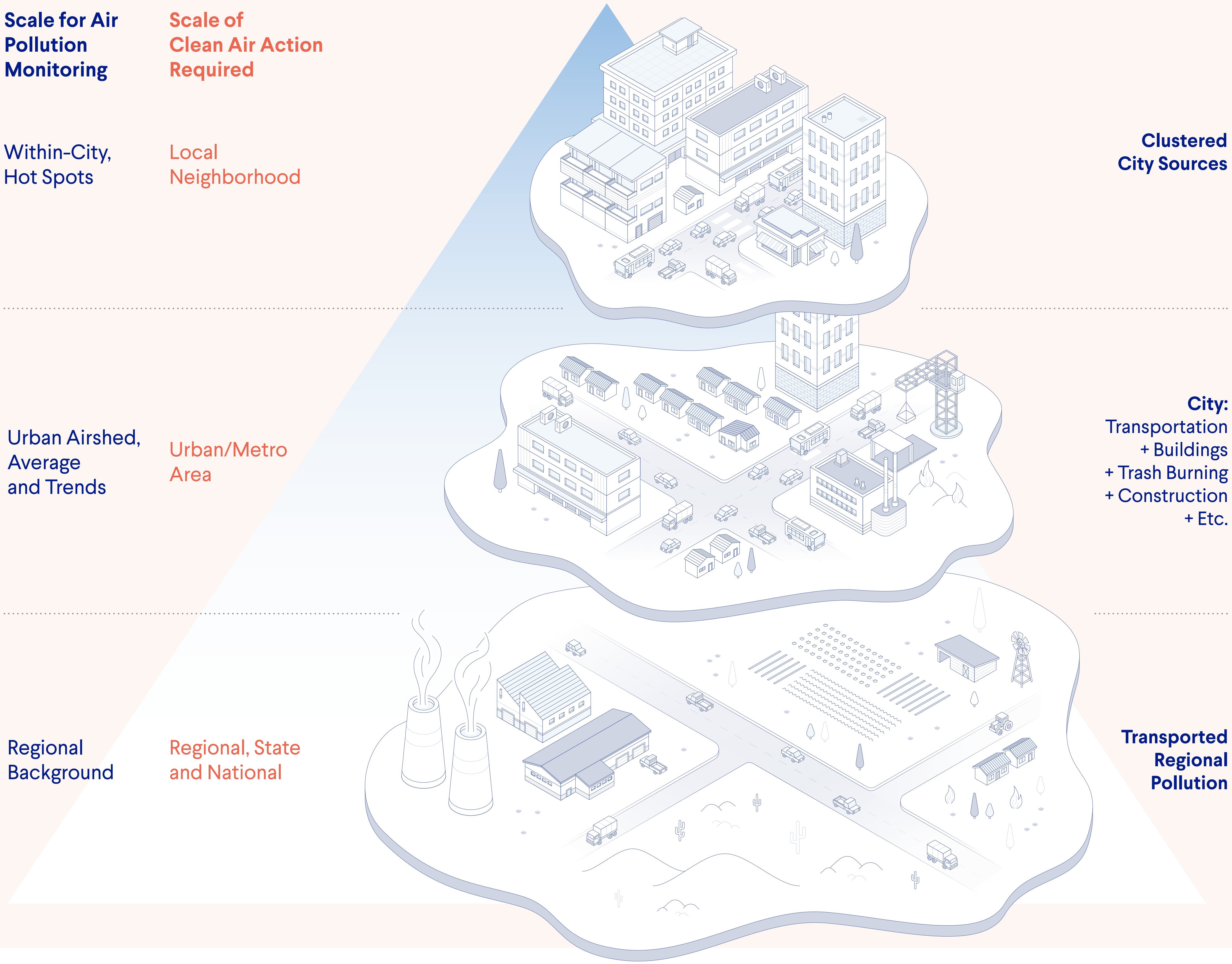
2.3
Air pollution variation by place and time

Figure 2c

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/



2.3
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.

2.3
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 2d
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 →

2.3
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 2d). 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.

2.4
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.

2.4 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 2, 3 and 6**.

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 2.**

2

2.4 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).

2.4 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 3**).

As government data quality and availability improve (see chapter 4) 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.

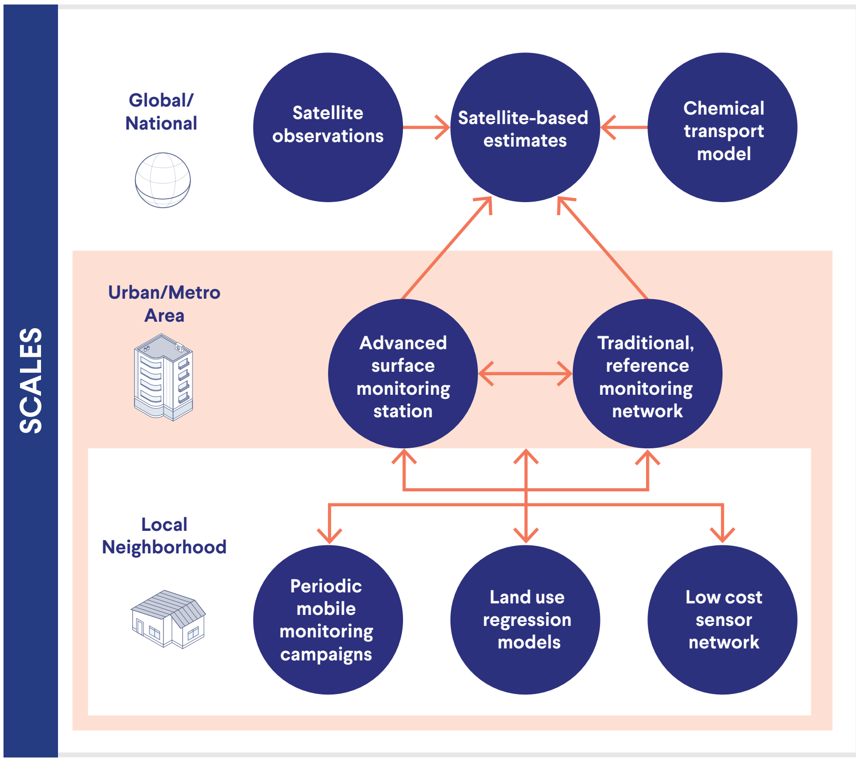
2.5
An integrated system combining conventional and innovative approaches

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 2**) 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

3

Assessing Emissions and Sources

3.1 Introduction: Essential data for clean air action planning

Simply put, while air pollution monitoring can point to the need for action, **emissions and source assessment is needed to know which actions will be most effective** by:

1. Understanding how emissions within and around an urban area affect ambient pollution concentrations throughout an urban area as they are transported and transformed in the atmosphere
2. Identifying the sources of air pollution that most impact population exposure and health
3. Characterizing the benefits of source reduction policies and actions

Decades of air quality management activity in high-income countries have produced extensive data on emissions and sources of air pollution, as well as complex systems for updating those data over time. Fortunately, innovations in source assessment are making data and tools available for cities in low- and middle-income countries to more easily identify the leading sources of pollution and rapidly point to priorities for near-term control (Figure 3a).

This chapter provides guidance for applying different emissions and source assessment data and approaches in phases tailored to a city's baseline capacity (Table 3b), emphasizing use of available data to set priorities and take actions to reduce emissions. As technical capacity grows, all cities can apply innovations, refine emissions, and source data to inform sustained improvements in air quality.

Figure 3a

Uses of air pollution source apportionment for clean air action plans

Implementing air quality action plans affects emissions, which affect air quality, pollution exposures and health. Because major air pollutants come from multiple sources, data on emissions and source contributions to ambient pollution are essential to identify priority actions and estimate benefits.

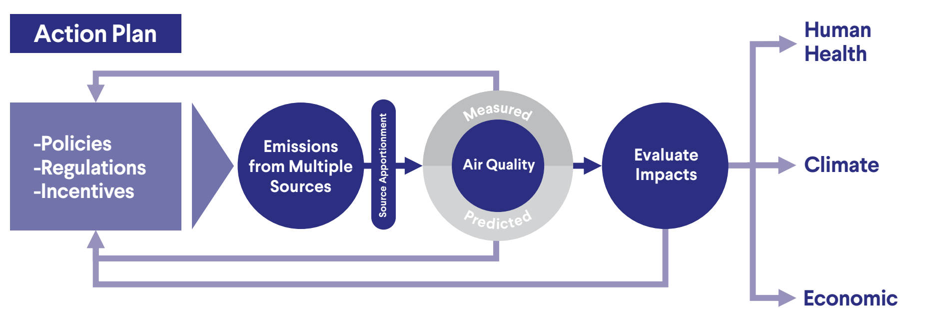


Table 3b

Air pollution emissions and source assessment capacity phases

1	2	3	4
Limited or none	**Minimal data for initial actions**	**Comprehensive data for sustained actions**	**Advanced data**
Data on sources of air pollution are limited or not routinely collected.	Official process is in place to assess and use all relevant available data— including international data—for initial action planning and emissions inventory development.	Source and activity data for priority emission sectors are routinely collected, improved, used and communicated.	Spatial and temporal resolution of emissions data are enhanced with local knowledge. Source contribution results from source- and receptor-based approaches are reconciled and improved.

3.2
Emissions and source assessment basics

Relevant reading for Source Assessment Phase

1 2

The terminology used in assessment of air pollution emissions can vary among technical experts and may be unfamiliar to many non-technical readers. Several relevant terms are explained in Table 3c.

To identify leading sources of air pollution, there are two complementary source assessment, or source apportionment, approaches: the source-based (or bottom-up) approach, and receptor-based (or top-down) approach. The source-based source apportionment approach depends on having an inventory of sources and their emissions and meteorology data that are used by computational models to simulate source contributions to ambient concentrations of air pollutants across appropriate time and spatial scales. In contrast, the receptor-based source apportionment approach collects ambient air filter samples, analyzes the chemical composition in the samples, and matches the chemical profiles with those of emissions from different fuels. Common to both approaches is the way the results are presented. Source apportionment yields estimates of the percentage and magnitude of different sources and sectors to the presence of an overall air pollutant. Source apportionment enables a city to know what share of its air pollution problem is attributable to transportation, industry, energy generation, burning, and different commercial activity. **Each approach has different strengths and limitations (refer to Annex 4 for details), and either can be used to identify priorities for initial action and further investigation**.

3

3.2 Emissions and source assessment basics

Table 3c

Air pollution source apportionment terms

Term	Definition
Source Apportionment (source attribution, source assessment)	Source Apportionment (SA) is the collection and analysis of data to estimate how much different sources of pollutant emissions (caused by human activity or natural events) contribute to ambient air pollution levels and human exposures. This is accomplished through two main approaches, described below.
Receptor-based ("top-down") source apportionment	A method of source apportionment that involves measuring the chemical composition of ambient air pollution samples and comparing the composition with known emission source profiles (see below) using one or more statistical models.
Source-based ("bottom-up") source apportionment	A method of source apportionment that involves using inventories and/or estimates of emissions for different sources in a geographic area, an emissions model to allocate the emissions by place and time, meteorology data and a chemical transport model.
Emissions factor	An emission factor is a representative value that describes the relationship between the quantity of a pollutant released to the environment with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., kilograms of particulate emitted per megagram of coal burned).
Emissions source profiles	Emissions source profiles are the average relative chemical composition of the emissions deriving from a pollution source, commonly expressed as the mass ratio between each species to the total emission. These profiles represent emissions from a category of sources (e.g. coal power plant) rather than the individual emitters.
Activity data	Information quantifying the activity of a relevant sector that generates emissions (e.g. amount of coal burned by an electric power station).
Direct emissions measurements	Direct emissions measurements are measurements of emitted pollutants by individual emitters. This type of measurement shows the amount and type of pollution expelled by specific sources.
Chemical composition (measured in air pollution samples)	The chemical composition in air pollution samples comprises the identity and relative amounts of each chemical found in the sample. (e.g. the amount of a $PM_{2.5}$ sample consisting of ammonium, sulfate, nitrate, elemental carbon matter, organic carbon matter, sodium, and silicon).

3.3 Emissions and source assessment: Objectives and approaches by phase

1 Identify, assess and use available data and tools

For cities lacking well-developed clean air programs and official emissions inventories or source apportionment, a first step is identifying available data and tools. International organizations and scientists have developed and made available global and regional anthropogenic (from human activity) and biomass emission inventories and emission factors (refer to section 3.4 on available data and source apportionment studies in **Annex 5** for details). In addition, researchers may already have conducted useful local source apportionment studies, including receptor-based studies (refer to section 3.4 on receptor-based apportionment). “Reduced form” models are also available to compare the impact of different control measures on ambient air quality in cities with limited capacity (refer to section 3.4 on reduced-form tools). These available data and tools can be applied to urban areas around the world to inform initial priorities for potential source control measures and improving data.

As discussed in Chapter 5, international and local technical partners can help governments assess available data and build capacity to use and improve it.

2 Establish an official emissions tracking and source assessment process, and develop procedures for data use

Using available data as a starting point, phase 2 establishes a process for building, improving and maintaining local emissions and source data. While it can be particularly challenging to develop an emissions inventory from scratch, working with a starting set of emissions data, either from localizing a global/regional inventory or adapting an existing inventory for greenhouse gases (GHG), can jump start the process. An important step would be cross-agency coordination of relevant data collection and management, for example among agencies developing GHG inventories and air pollution emissions data (refer to Chapter 5 on how to organize for clean air action).

At the same time, planning monitoring enhancements to support receptor-based source apportionment can be initiated (refer to section 2.4 on “Advanced particle surface monitoring stations” for more details). Data enhancement can occur in tandem with development and improvement of clean air action plans. As has occurred in high-income countries, querying and using even limited emissions and source data for policy and regulatory purposes will help reveal the importance of continuous data improvement.

3.3
Emissions and source assessment: Objectives and approaches by phase

3 Sustain routine collection, improvement and use of emissions and source data

At this phase, it is a routine, ongoing process to collect emissions data, periodically update inventories, and use the source-based modeling to assess policy options and impacts. Receptor-based source apportionment studies should be underway along with periodic monitoring and source-based campaigns. Air pollution source information is communicated to the public. The city's capability at this phase is functionally similar to that of state- or provincial-level programs in high-income countries.

4 Build advanced, highly space- and time-resolved emissions, source and forecasting capability

Innovative approaches, open source data and increases in computing power are enabling the development of emissions and source apportionment models with high spatial resolution (e.g. 1 km^2) that can be used to model impacts of policies on ambient air quality at a neighborhood scale (refer to section 2.4 on "high-spatial-resolution monitoring"). As with high-resolution air quality monitoring, this can help to better account for population vulnerability to harm from air pollution (32) and to evaluate spatially focused controls, such as low-emission zones.

3.4
More about emissions and source assessment approaches

Relevant reading for Source Assessment Phase

1 2 3 4

Source-based or “bottom up” source apportionment

The source-based source apportionment approach utilizes inventories of the sources and their emissions, meteorology data, and computational models to simulate source contributions to ambient concentrations of air pollutants across appropriate time and spatial scales. The source-based approach can assess potential future impacts of sectors and evaluate control measure impacts on air pollution across an urban area (Figure 3d).

Relevant reading for Source Assessment Phase

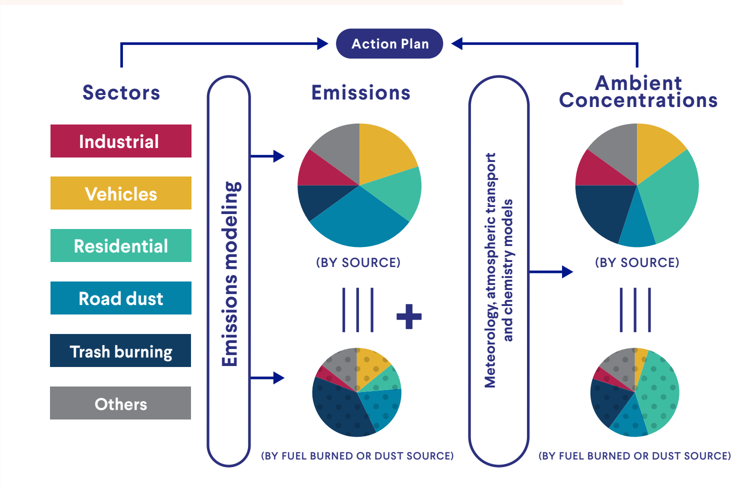
2 3

Developing and maintaining local emissions inventories

The development of an emissions inventory for source-based source apportionment approach requires data on emissions factors, emissions source profiles, activity data (e.g., fuel sales, building data), and—ideally—direct measurements of the amount and composition of emissions and both fuel- and source-based data. Such emissions data may be directly measured and generated as a result of regulatory programs (e.g., permitting, inspection and maintenance programs), often for large facilities, and may be accessed through partnerships among local and national government agencies. All emissions inventories involve estimates, assumptions and extrapolations for at least some sources.

Figure 3d

The source-based (bottom up) approach to source apportionment



Emission sources are grouped into sectors, and available data on quantity, activity and location of sources are combined with emission factors and models to estimate the quantity of different pollutant emissions by sector, location and time. For sectors involving fuel combustion, the emission quantities by fuel is also estimated. Other sources involve mechanical processes that produce dust. Models can combine emissions and weather data to predict how pollutants are transported and chemically changed, estimating the share of ambient pollution concentration by sector and by fuel. The impact of sources on ambient pollution concentrations at different locations can be used to estimate population exposures and health impacts by source. The results can be used to evaluate clean air action plans.

Emission data may also be estimated, although with greater uncertainty, where there are less reliable activity data and lack of well-developed air pollution regulations. Obtaining useful activity data is a particular challenge, especially for sources that are not large facilities. Creative approaches have leveraged local surrogate data, such as from commercial maps and traffic data. The Air Pollution Knowledge Assessment (APnA) city program in India and New York City Community Air Survey (refer to Chapter 6, New York City case study) are examples of enhancing the quality and resolution of local emissions data.

In some instances, cities may already have existing or newly developed GHG inventory using standardized frameworks [e.g., GHG Protocol for Cities (72)], but limited or no emissions inventory for air pollution. In those cases, GHG inventory can act as a good starting place for building an inventory for air pollution, as many GHG also contribute to air pollution, and activity data collection is similar for both inventories.

3

3.4 More about emissions and source assessment approaches

Once a workable starting set of emissions data has been assembled, it is essential to develop protocols, processes and standards for ongoing data collection, inventory updates, data management, sharing and reporting (see Chapter 4 on Data Accessibility and Chapter 5 for Organization for Actions).

The source-based approach requires highly specialized technical and computational skills. Both the emissions inventory and meteorology data for the year with the latest or most reliable data should be obtained (73). The data then act as input variables to computer numerical models known as the chemical transport models or dispersion models, which simulate the transport, transformation and removal of gases and particles in the atmosphere. An example of such a model is the Comprehensive Air Quality Model with Extensions (CAMx) (74) used in the APnA city program.

Reduced-form tools are available to simplify the complex source-based modeling. Tools like LEAP-IBC (75) and FASST (76) that do not need chemical transport modeling are also available to provide initial source results and quick comparison of a large number of different policy scenarios, before full-scale models are applied in more detailed analysis.

Another important feature of the source-based approach is the ability to assess the impacts of non-local emissions and transported pollution on urban air quality. While many emissions inventories are at the city scale, regional emissions inventory can be developed and analyzed along with the city-level inventory using the chemical transport model (nested model) to quantify non-local emissions that affect the urban area. The regional model—usually with a coarser grid—provides the boundary conditions to the urban area, which is later translated as imported pollution originating from outside the airshed. Satellite data can also be used to identify pollution plumes that travel long distances. Regional and global model forecasts can also be used for this purpose (refer to **Annex 6**).

Relevant reading for Source Assessment Phase

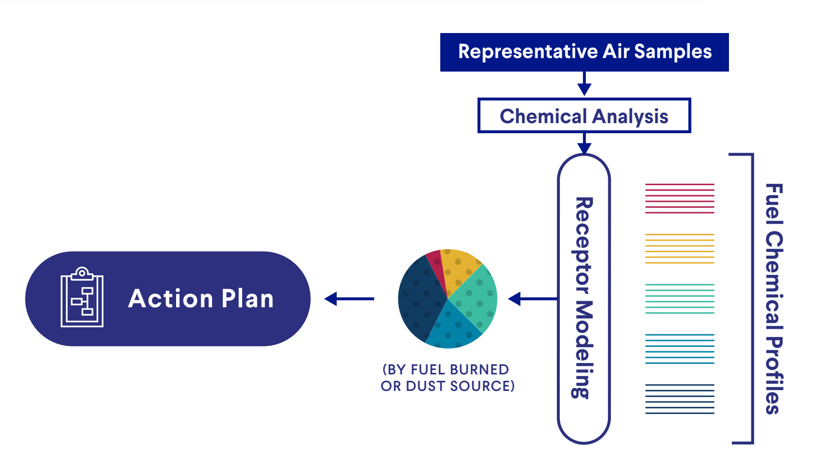
3 4

Using innovations and local data to develop advanced, high-resolution emissions and source-based models

Available emissions inventories often have limited temporal resolution (e.g., yearly) and coarse spatial (e.g., at national scale only), and therefore may not enable high-resolution urban- and local-scale studies. In these cases, data from official and other sources on local source activity or surrogates—such as fuel use and quality, vehicle fleet mixes and counts, traffic, power stations and industries—can be used to supplement and improve available local emissions data to provide more realistic and accurate emissions inventories. The APnA city program (26) is an example of this approach, and has already been used to develop high-resolution emissions inventories, atmospheric models and forecasts for more than 50 large cities across India (26,77). Another example is New York City, where local data on building boilers, fuel types and building interior space were used to replace and spatially allocate county-level emissions data that were developed according to national inventory

3.4
More about emissions and source assessment approaches

Figure 3e
The receptor-based (top down) approach to source apportionment



Air samples are collected at multiple locations and times to represent an urban area of interest at different times of year. $PM_{2.5}$ filter samples undergo chemical analysis to determine their composition. Statistical models compare chemical composition of $PM_{2.5}$ samples with chemical composition profiles of emissions from different fuels burned and dust sources in the area to estimate the share of ambient $PM_{2.5}$ sampled coming from different sources. This information can be used to identify priority fuels and sources for control in clean air action plans.

protocols (32).

In addition to stimulating source contributions at the baseline year, the source-based approach can incorporate real-time or projected meteorological data, ground-level monitoring or satellite data and dynamic emissions models to support short-term forecasts (one to three days) of air pollution levels. Forecasts can be used for public health advisories (see Chapter 2 on Ambient Air Monitoring) and to trigger short-term mitigation measures (e.g., agricultural burning bans and limits on private motor vehicle driving).

Moreover, such space- and time-resolved forecasting models can be used to predict areas with the highest pollutant concentrations (and exposures) and the contributing sources and identify the most effective locations for air quality monitors intended to reflect local hot spots and for source apportionment.

Relevant reading for Source Assessment Phase

1 2

Available data from emissions and source apportionment studies
An example of global emissions inventory available is the Emissions Database for Global Atmospheric Research (EDGAR), which provides past- and present-day air pollution emissions data from major sectors at global, regional and country levels (78). To inform locally relevant sources, regional inventories, such as Diffuse and Inefficient Combustion Emissions in Africa (DICE-Africa), and Multi-resolution Emission Inventory for China (MEIC), could be used (79,80). Also, the APnA city program in India has already developed emissions inventories and source apportionment information for a growing number of Indian cities (information available at www.urbanemissions.info) (26).

Besides emissions inventories, emissions factor databases detailed by source and fuel types are available. Those databases include the United States Environmental Protection Agency (U.S. EPA) AP-42 (81) and the European Environmental Agency Air Pollution Emission Inventory (82); though caution should be exercised when applying these emissions factors in developing countries because their technologies and practices may differ from those used in high-income countries. Refer to **Annex 5** for a list of resources on global and regional emissions inventories and emissions factors.

3

3.4 More about emissions and source assessment approaches

Relevant reading for Source Assessment Phase

2 3 4

Receptor-based or "top-down" source apportionment

Receptor-based source apportionment approach measures ambient air pollution concentrations by collecting air filter samples at specific locations, analyzes the chemical composition in the samples, and compares and matches the chemical profiles with chemical signatures of emissions from different fuels using statistical "receptor" models (Figure 3e).

Findings from the receptor-based approach are representative of the sampling locations and the time period during which a sample is collected. A city or region may need one or more sampling locations strategically placed—often collocated with high-quality reference or other air monitors to capture the population exposure to both the regional transported pollution as well as pollution from local sources that are unevenly distributed (refer to section 2.4 on "Advanced particle surface monitoring stations" for more details). This approach is backward looking, and air filter samples should be collected over multiple cycles—each 8-hour, 24-hour or longer cycles depending on the type of sampler—that cover various time periods to represent different times of year with different source contributions and weather patterns.

Once the filter samples are collected, they undergo chemical analysis to determine the concentrations of individual chemical species and elements. This process requires access to sophisticated laboratory equipment, often found in universities and national environmental ministries. The specificity of source identification depends on the chemical analyses used, with elemental analysis and some organic speciation providing more detailed profiles than simpler methods used to measure black carbon and some ions (83). The receptor-based approach also requires knowledge of chemical signatures representing various fuels (e.g., petrol, diesel, gas, coal, wood, dung, plastic and other solid waste, or mechanically generated particles, such as windblown dust and saltwater aerosols), which can be statistically matched to estimate how much each of these contribute to the ambient pollution samples. For cities with limited or no information on local chemical signatures of air pollution sources, one can reference the U.S. EPA's SPECIATE database, which is a repository of PM chemical profiles of air pollution sources (84). A limitation of the receptor-based approach is that it often cannot distinguish emissions from different sources that burn the same fuels, nor can it locate specific sources from space (73).

The receptor-based approach does not need to be conducted annually but can be repeated periodically to check for model assumptions and identify potential discrepancies with findings from the source-based approach.

3.4
More about emissions and source assessment approaches

Relevant reading for Source Assessment Phase

1 2

Available data from receptor-based source apportionment studies
For low- and middle-income countries with limited or no receptor-based source apportionment studies or chemical signature of emissions sources, existing databases are available to help understand such an approach. WHO created a database in 2015 to document over 400 source apportionment studies for ambient PM conducted in 51 countries worldwide (85). While the database may not have the most up-to-date studies, it provides a good starting point for understanding source contributions from the receptor-based source apportionment method in some cities/countries. In addition, local or international researchers may be conducting receptor-based studies not in the WHO database or not yet published.

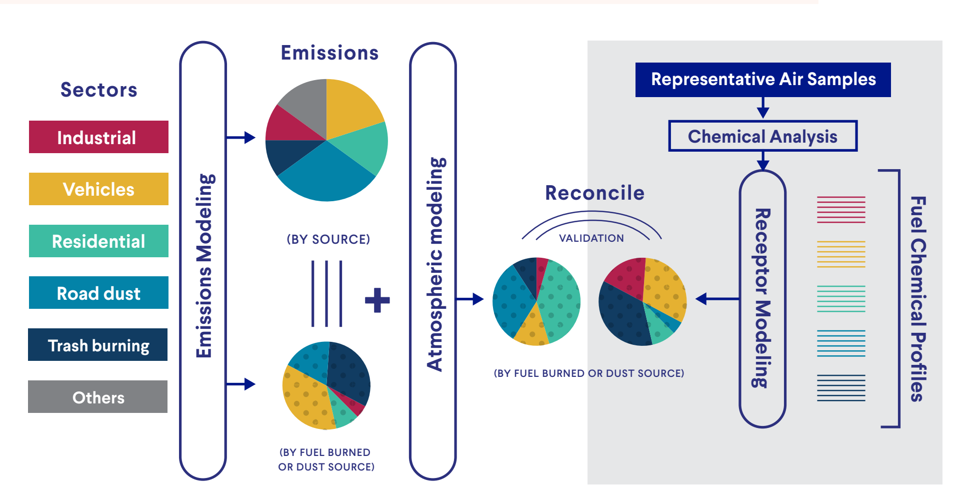
3.5
Combining source assessment approaches to improve data

Relevant reading for Source Assessment Phase

2 3 4

Using and comparing results from both source-based and receptor-based approaches allows assessors to identify consistencies and discrepancies between results produced by the two approaches; this will increase confidence in data on some leading sources and priorities for control, while plans and priorities for collecting new emissions and activity data and refining existing data can be developed (Figure 3f). Examples of use of receptor-based and source-based source apportionment approaches used in different cities are discussed in more detail in the case studies in Chapter 6.

Figure 3f
Combining source-based and receptor-based approaches to improve data



Both methods rely on imperfect models, assumptions and underlying data. Discrepancies between results from the two methods can be used to inform checks and improvements of underlying data.

City case studies of monitoring innovations in action:

New York City

Hong Kong

Beijing

Bangkok

Kathmandu Valley

Accra

4

Data Availability, Accessibility, and Use

4.1 Introduction: The benefits of open, accessible data

Making air quality data open and accessible to official and nonofficial users is critical to ensuring that cities can:

1. Build trust in government's desire to improve air quality, engage public/stakeholders and increase support for clean air action;
2. Promote the use of a common set of reliable data from all official and nonofficial sources for multiple applications to inform government officials, agencies, civil society groups, researchers and other air quality stakeholders; and
3. Use integrated data to inform policy analyses, monitoring and evaluation, public health and other research, and private sector applications.

An increasing number of cities, states and countries are making their data publicly available, as they realize the broader benefits of increasing public access to these data. At the same time, nonofficial, but reliable data generated by academic researchers, NGOs and others may be available to fill data gaps where official air quality monitoring is limited or nonexistent. This chapter provides guidance for increasing the availability, integration, and use of government-generated and unofficial (collected by researchers and others) air quality data for both technical (research and regulatory) application, as well as to clearly inform non-technical stakeholders, including the general public and civil society organizations.

As with air monitoring and emissions and source assessment, cities vary widely in their current capacities, policies and practices for making air pollution data open and accessible. The table below can be used to assess the capacity for open data in a city and serve as a guide to using a phased approach to making improvements in data availability, accessibility and use.

Table 4a

Data availability, accessibility and use - capacity phases

1	2	3	4
Limited or none	**Minimal data for initial actions**	**Comprehensive data for sustained actions**	**Advanced data**
Official air quality data are not collected or not reliable or not reported publicly.	Reliable official data on $PM_{2.5}$ are collected and publicly reported (e.g. in static web pages); historic, machine-readable data (e.g. CSV files) may be available on request.	Reliable official data are available online in human- and machine-readable formats.	Integrated, reliable, interoperable data from official and non-official sources are accessible in human- and machine-readable formats.

4.2
Open data and data use basics:
Defining open, accessible data

Relevant Reading for Open Data Phase

1 2

Fully open and accessible air quality data are provided in both raw and analyzed formats with appropriate access, metadata and explanatory information for different stakeholder audiences, broadly categorized as:

- **Non-technical audiences**, including elected officials, the general public, media and advocacy organizations who require data to be succinctly summarized, analyzed, and communicated via easy-to-understand measures, alerts (where warranted), and simple graphical displays of information. For example, estimates of air pollution levels and trends, as well as resulting short- and long-term impacts to health should be simply and clearly communicated to the public and key decision-makers.
- **Technical users**, including regulators and researchers, need access to time-resolved pollutant levels in well-documented, computer-readable data and metadata formats. Ideally, air quality data should be provided in a format that can be linked with relevant demographic and health data to clearly translate information on air quality levels into associated health impacts.

Open, accessible *official* monitoring data promotes the expanded use of data for other applications, including public health research, policy analyses, and private sector applications. For example, seven out of 10 of the most cited large-scale epidemiologic studies on the health effects of air pollution have relied on government ambient monitoring station data, and results have influenced national policies and international guidelines. In the same way, open, accessible *nonofficial* but reliable data collected for research or other purposes can be useful to governments for assessing air quality and informing local clean air measures.

By itself, internet publishing of daily air quality index (AQI) reports or annual summary reports comprises only minimal and very limited data availability and is not sufficient to fully meet expectations of transparency or to support a wide range of end users.

4

4.3
Creating and using open and accessible data:
Objectives and approaches by phase

1 Government commitment to collecting and sharing official air quality data

A commitment to collecting reliable official air monitoring data with clearly documented quality assurance and quality control measures in place is an obvious first step and should be paired with a commitment to creating open and accessible data. Sharing incomplete or unreliable data will only lead to confusion and/or mistrust of official data. This is particularly true since it has become increasingly easy for members of the public to compare official data with open-access, nongovernmental information that documents a serious air pollution problem, including satellite-based estimates and air pollution monitors on foreign embassy grounds. While much of these data are credible and highly quality controlled, the internet also provides widespread and increasing access to data from less reliable, unvalidated data from a range of sources, including lower-cost consumer sensors, resulting in widespread communication about air quality which may not be well grounded in facts (86).

As planning and implementation of official monitoring is taking place, data sharing policies, plans and data management capacity for making official air quality data publicly available in a transparent manner should ideally be developed in parallel. Such policies will require support at the executive level in government, which should be assessed and, if necessary, built, as part of the overall clean air organization for action process (refer to Chapter 5). As part of this process, potential barriers and solutions to making data open and accessible should be assessed (refer to section 4.4).

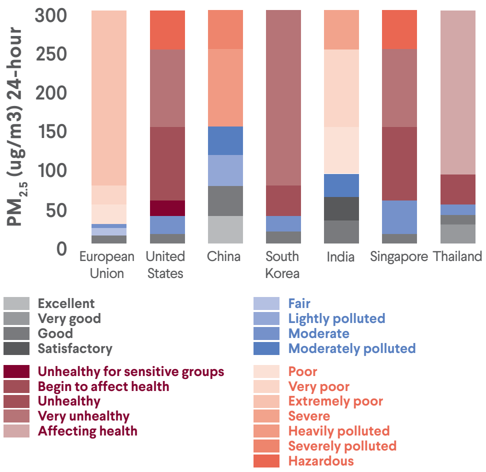
In many cities, researchers, NGOs or other entities (such as foreign embassies) may be collecting reliable air quality data. Such entities should be engaged in developing data-sharing agreements and technical standards, both as data providers and potential users.

Short-term air pollution episodes and advisories

Public warning systems, such as those based on an air quality index (AQI), have been used for decades. The AQI is generally a ratio of a short-term air pollution measured or forecast level to a short-term standard. More recently, the AQI has been widely adapted in low- and middle-income countries. While useful for raising awareness and promoting behavior change, AQI-based warning systems have serious limitations for protecting public health, including little evidence of population-level or sustained health benefits. In highly polluted cities, large segments of the population may have little or no ability to reduce their exposures (38). Furthermore, the AQI does not consider multi-pollutant effects and ignores health effects observed below even stringent regulatory standards for single "index pollutants" (39). Implying that pollution levels below regulatory standards mean that the air quality is "good" is especially misleading where the AQI is based on feasibility-based targets, rather than a truly health-based standard (Figure 4b – AQI).

To address some of the AQI's limitations, Canada's Air Quality Health Index, also implemented in Hong Kong, reflects multi-pollutant health risks below air quality standards and distinguishes messages for populations with different susceptibility to harm (40,41).

Figure 4b
Air quality index (AQI) categories based on $PM_{2.5}$ concentrations, selected countries



Because the AQI is commonly based on a regulatory air quality standard, differences in air quality standards and local practices lead to different cut points and terms for the AQI. The AQI categories are most misleading where regulatory standards are mainly based on feasibility, rather than evidence about health effects.

4.3
Creating and using open and accessible data: Objectives and approaches by phase

2 Routine communication, increased access and developing interoperability of relevant air quality data

During this phase, timely, official air quality data should be easily available in a format suitable for non-technical air quality stakeholders, including the general public, and accompanied by explanatory information about health impacts and advice, sources and actions taken or planned by the government (refer to section 4.3 on "Short-term air pollution episodes and advisories"). Public air quality information should include both daily or near-real-time information, including air quality health advisories (sidebar) as well as periodic (e.g. annual) summaries.

For technical users, data for research and modeling should be compiled and made available on request or for download in a machine-readable format. If not already in place, active efforts will be needed to develop standards and systems to ensure interoperability across different sources of data, laying the groundwork for development of an integrated system (refer to Figure 2e).

3 Expanded access, integration and communication of air quality data

Once systems are in place to make routine, official air monitoring easily accessible for non-technical and technical users, data use, linkage and reporting should expand to improve public information, such as air quality forecasts, if available. In addition, summary reports should become more policy relevant, link air quality with leading sources of pollution and ideally provide estimates of air pollution population health burden and health benefits of clean air policies. At this phase, additional data can be integrated and made available in human- and machine-readable formats, such as emissions and source apportionment data, facility permits and inspection data.

4 Developing an advanced integrated air quality data system

When official air pollution data are fully open and accessible in human and machine-readable formats, higher spatial resolution monitoring may be able to support more granular reports and maps. Integration in a single platform of reliable nonofficial data, such as from research monitoring and models, traffic data, greenhouse gas emissions and remote-sensing estimates. More complex near and long-term forecast models of air quality may be automated and publicly available. It should be noted, however, that this level of intense forecasting is not undertaken even in many countries with very advanced air quality monitoring systems, and the practical application of model results should be considered before allocating additional resources.

4

4.4
Creating open data:
Barriers and solutions

Relevant Reading for Open Data Phase

1 2

Despite multiple potential benefits, reliable official air pollution data are not publicly accessible in many countries

Among countries with active official monitoring, access to government-generated air quality data varies significantly. Based on information compiled by OpenAQ, an open source platform, there is some degree of publicly available air pollution data across Western Europe, North America, much of Asia and much of Latin America. China, Nepal, India, and others have also made their ambient ground monitoring air quality data open to varying degrees. Gaps in publicly available data—only sometimes due to a lack of official monitoring—are seen across much of Eastern Europe, Africa and the Caribbean/Central America region.

Even in many countries with publicly available data, there can be limits on fully accessible, machine-readable data. In the most fully open cases, sub-daily resolution (e.g. hourly) air quality data are provided on current (e.g. near-real-time) and historical timeframes through both human-readable (e.g. a website) and computer-readable (e.g. FTP server or Application Programming Interface) forms. In less open cases, summary data are provided in tabular or graphical format on a website, perhaps only in a country-specific air quality index form. In increasingly rare cases, air quality data are not made available at all, or only by formal request to an agency official.

Relevant Reading for Open Data Phase

1 2

Cities and countries can expand open air pollution data by identifying local technical, social/political or financial barriers and deploying tailored solutions

(1) Technical Literacy and/or Capacity Barriers: A lack of understanding about the true definition of "open data" can be a barrier, as governments sharing air quality index (AQI) data to the public on a daily basis may believe they are already providing data in an appropriate format. Governments may also lack the information technology capacity and infrastructure to manage and make air quality data routinely available.

Valid concerns about sharing data of uncertain quality can impede open access efforts. Inaccurate data can erode public trust, generate unnecessary concern and/or miss critical air quality events. Overcoming this barrier requires establishing and ensuring (ideally through independent audits):

- Clearly documented, automated procedures for ensuring data quality and completeness are in place; and
- Verification that these procedures are being routinely and accurately undertaken and documented.

4.4
Creating open data:
Barriers and solutions

Table 4c
Barriers and solutions to open air quality data

	Barriers	Solutions
Technical	Data not easily shareable format or available with sufficient detail	Partnering with technical experts; canned routines; available scripts; machine readable, station-, pollution-, time-resolved data available
	Metadata and QA/QC are not accessible, data quality uncertain	Using and disseminating metadata standards, implementing, documenting and sharing data QA/QC and audits
	Data unavailable in timely format	Make data regularly available; automate sampling and data processing; combine real-time monitors with integrated sampling
Social/Political	Disparate data collectors; lack of data sharing policies	Coordination and data use agreements; open data policy changes and development
	Fear of data misuse	Provide clear data documentation; proactive data release and interpretation; counter messaging in the event of misinterpretation
	Fear of negative press; fear of public recrimination	Promoting clean air action plan; involving health ministries/experts to develop fact-based health info; training journalists
	Lack of recognition/credit for data	Data licensing
	Lack of open data culture	Develop open data policies; leadership expectations and incentives for data to support policy
Financial	Fines for air pollution exceedances that discourage open data	Changes to enforcement policies
	Fee structures for accessing data	Charge for data analytic service rather than data
	Insufficient capital and ongoing funds for data systems	Incorporate open data costs in monitoring budgets and proposals

4

4.4 Creating open data: Barriers and solutions

Overcoming these technical barriers requires development of data standards, standard operating procedures and systems. Partnering with outside experts for technical assistance and training will often be needed.

(2) Social and Political Barriers: Organizational hierarchies or silos may also impede coordination needed to implement open data (87,88). These barriers are reinforced in settings where no clear open data policies exist. For example, technical experts within government agencies may not have permission to obtain relevant data collected by other government agencies, or data may be maintained by different agencies in a way that hinders interoperability and integration. While this is seldom intentional or "by design," political commitment and resources are required to break down these data silos for a more streamlined approach to data management.

In some cases, there may be anxieties around data being misused, or misattributed, or questioned if they are made open. Making data open can be perceived as creating an opening for negative reactions by the public without the means to address them. Thus, in cities lacking a clear understanding of the sources of air pollution and a realistic clean air plan and a capacity to control emissions, limiting access to official air pollution data may be a reflexive strategy. Communicating a commitment to a clean air action plan along with openly sharing air quality data is a constructive, proactive alternative to this defensive approach. Failure to provide open data generally creates more public concern and mistrust, as it is often perceived as downplaying the seriousness of the problem and/or delaying action.

Another potential barrier to open air quality data can be a lack of expertise to accurately communicate the health effects of air pollution. Active collaboration with the public health agencies and nongovernmental experts can build capacity to effectively communicate these and to provide guidance on effective policies and personal strategies to reduce risk over the short and long term. Journalist training by independent organizations can be helpful in promoting fact-based information that can build support for clean air actions.

(3) Financial resources: In low-resource settings, investing in data-sharing capacity and infrastructure may be a secondary concern. Some government agencies fear that the provision of open data will undermine existing revenue streams, especially when data are currently available for a fee. Given the relatively modest financial and human resources cost required to create and maintain machine-readable data-sharing mechanisms, governments should be encouraged to invest in data sharing architecture, and external funders should also be encouraged to require the public availability of data as a condition for funding to strengthen air quality monitoring systems.

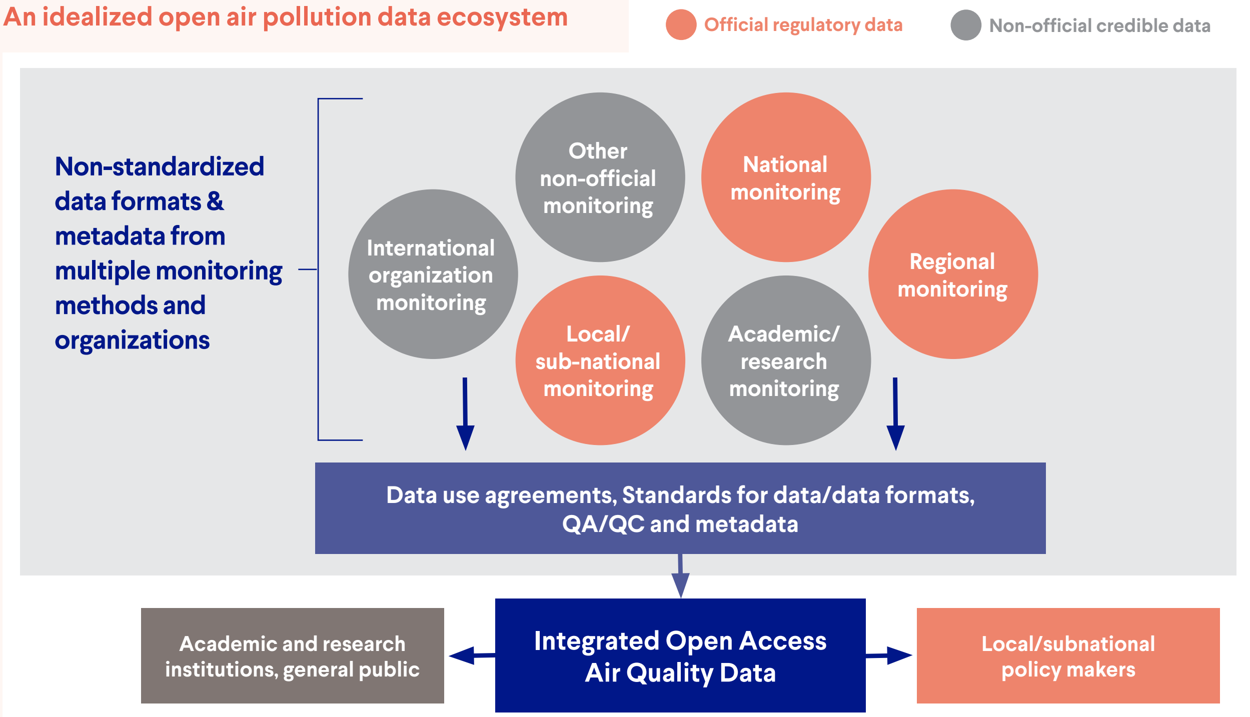
4.5
Building an advanced, open, air quality data ecosystem

Relevant Reading for Open Data Phase

1 2 3

An ideal open-air quality data ecosystem should maximize the utility of both official and nonofficial reliable data for both official and nonofficial end users. This is analogous to the design of effective health management systems, where all data for a single patient may be accessed from a common source by the patient and their healthcare providers to track and manage the patient's health. Multiple applications can be supported by a technical approach and platforms that address a range of data sources, formats, and users.

Figure 4d
An idealized open air pollution data ecosystem



An ideal system should accommodate data from multiple official and reliable non-official sources.

The system should be able to:

- Incorporate data from multiple official government and credible, nonofficial, nongovernmental data sources;
- Share data in fully open, computer-readable formats that enable the data to be harmonized and integrated (e.g. aggregated and converted into the same format);
- Make air pollution data available in transparent, open layers including:
  - near-real-time raw data
  - modeled estimates (e.g. from remote sensing or land-use regression)
  - more user-friendly synthesized forms
  - relevant metadata; and
- Enable open-source community tools and applications serving both government and nongovernment users.

4

4.5 Building an advanced, open, air quality data ecosystem

Ideally, to maximize accessibility, raw data and corresponding metadata (e.g. land use around station, instrument details, etc.) should be made available in a standard digital format, such as a public FTP server or an open and well-documented API for both transparency and increased utility to multiple technical and scientific sectors. An air monitoring API should include, at minimum, the following elements: parameter pollutant name, concentration, units of parameter measurement (e.g. μg/m^3), date/time stamp, time-average that interval measurement was made over, geographic coordinates of station, station name, attribution/name of source.

Listed below are several data sharing platforms—some city-specific and some global—that have been developed and provide some features of a fully open ecosystem:

1. **SIATA—Medellin (Colombia)** (89) and **US EPA AirNow (United States)** (90): Near-real-time ambient air quality data are shared via a public-friendly user interface as well as an open API and/or FTP server. This enables the data to be ingested into technical tools, as well as harmonized with other data sources on other platforms.
2. **Central Control Room for Air Quality Management—All India** (91): Web portal to visualize continuous air quality monitoring station operational status and select and download data for further analysis by site and parameter.
3. **Londonair** (92): A comprehensive web data portal for the London Air Quality Network, providing access to real-time, forecast and past data, data visualizations and explanatory information for London and Southeast England. It is managed by King's College London on behalf of local authorities and other organizations that fund the monitoring and data management. Londonair is among the most flexible and user-friendly urban air quality data portals.
4. **New York City Community Air Survey** (United States) (93): The **NYCOpenData** (94) platform provides an annually updated dataset and metadata for 300 meter resolution and raster level estimates for multiple pollutants derived from land-use regression models. Neighborhood-level summary estimates of these data as well as charts and tables of regulatory monitoring data are available in an interactive **NYC Environmental and Health Data Portal** (95).
5. Globally Harmonized Data Sharing: **OpenAQ** (96) provides a back-end/machine-readable data feed for 10,000+ stations in 70 countries, harmonizing multiple government sources to facilitate data analyses and development of open-source tools to further utilize data.

City case studies of open data in action:

New York City

5

Organization for Action

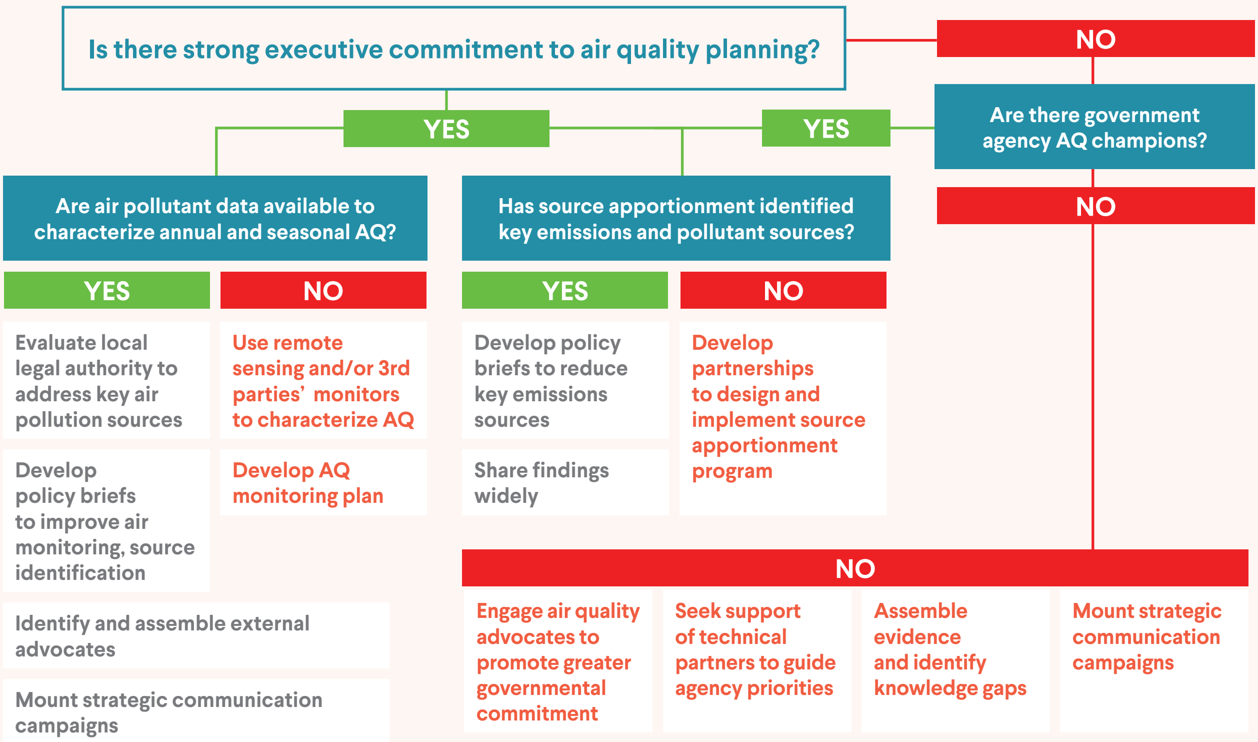
5.1 Introduction: The importance of government executive leadership and coordination

Successful development and implementation of effective air quality management requires more than just having the right data and technical knowledge; political will, government leadership, an intersectoral approach, and coordination of partners are all essential to:

1. Build and sustain systems to monitor air quality and assess sources;
2. Use data to establish priorities and plan control measures;
3. Implement and assure clean air actions; and
4. Communicate progress, health risks, and benefits of controls to sustain public support.

In highly polluted urban areas, initial city-led clean air action planning calls for a more flexible approach than conventional air quality management planning in high-income countries. Regardless of the local situation, the starting point of organizing for clean air action depends on the level of government engagement and commitment. Securing commitment from the executive level (city mayor, governor or equivalent) is necessary to make real progress, but if commitment is lacking, steps can be taken to help build the case for action and to drive demand for greater engagement. The flow chart below (Figure 5a) provides an overview of next steps to enhance this commitment for each phase of engagement, and how assessing technical capacity and using data contribute to building support for government action and informing policy. The city case studies appended to this guide offer examples of how cities at various stages of air quality understanding and political commitment took specific initial actions to move forward.

Figure 5a
Starting points and steps to organizing for clean air action



5.2
Building and sustaining government commitment: Four critical political goals

Identify and champion political leadership. At a city level, mayors or other executives have significant leverage over discourse and the direction of resources. Legislative bodies may also lead the political process to move a city toward cleaner air. Their direct engagement is critical. If their engagement is absent, champions can typically be found in technical agencies that are fulfilling narrower missions around transportation, planning, energy and economic development.

Secure and sustain political commitment. Political commitment may be initiated by strong leadership but is more likely to survive leadership change when it is sustained through decentralization of expertise, ongoing public engagement, sharing of progress and continued justification for investment of human and fiscal resources. Political commitment occurs when the issue of air quality becomes an accepted and explicitly articulated goal, just as most cities already acknowledge and are working toward improved water quality, better roads, waste handling, job opportunities and education.

Assess current technical capacity (refer to chapters 2, 3 and 4), to identify and develop relevant expertise within government agencies and use technical partnerships with research institutions and/or expert consulting firms to build capacity quickly. Experienced, expert personnel working within public agencies supports continuity of data and knowledge generation and enables the tasks of air quality management and improvement to become embedded in the missions of permanent government entities. In many instances, it may be appropriate for agencies to outsource technical work via formal agreements with academic or other partners. Examples of such partnerships are the GeoHealth Hub in Addis Ababa (97), London Air Quality Network by King's College London (92), Marine Emission Inventory by the Hong Kong University of Science and Technology in Hong Kong (98), as well as the New York City Community Air Survey by Queens College (93) (refer to the Hong Kong and New York City case studies for more details). But even if such partnerships are used, health, environment, transportation, energy and other agencies should remain in the lead on data dissemination, policy development and evaluation. To advance governmental engagement, partnerships can include secondment of personnel to government agencies from academic or other technical partners.

Build and engage a public constituency for ongoing clean air action. All environmental health policies can be perceived as having winners and losers. Promoting and implementing health and environment-protective policies costs money, and frequently involves temporary disruptions to the political and budgetary status quo. Taxation, shifting subsidies, expending funds on improved air monitoring, regulating emissions, mandating clean fuel and the like all depend on the public's belief that these shifts are beneficial, necessary, and better than alternatives. Private citizens, advocates, NGOs and other organizations need and deserve data and engagement; and their input should be solicited and considered. In some settings, strategic communication efforts will need to address widespread misperceptions about air pollution effects, sources and solutions (99). Just as capacity for technical aspects of air quality management may require assistance from outside expert partners, strategic communications assistance may be needed to support an ambitious clean air agenda.

5

5.3
Organization for Action:
Strategies and resources

City governments have important levers and authorities to promote clean air

An important step in developing a city clean air action plan is assessing a city's current authority to regulate or take other actions that can reduce local emissions. While the division of authority between local, state and national governments varies widely, in most cases, cities can use one or more of the following levers to support clean air action.

1. Cities can act to control sources within their jurisdiction, for example by investing in clean public transit and giving public transit vehicles priority over private motor vehicles on city streets. They may have authority to set clean technology standards for other city-owned or regulated vehicle fleets, or by investing in improved solid waste management to reduce trash burning;
2. City executives can leverage their authority to convene often siloed agencies to align relevant initiatives and policies, such as climate change mitigation, that can influence clean air. For example, the development of a city's climate action plan is an opportunity to assess air pollution levels, local sources, and costs and benefits of alternative control strategies (e.g. electric vehicles vs clean fuels and world-class emissions controls). Other examples are public transit investments and subsidies to promote uptake, improving walkability and cycling infrastructure as well as zoning and housing policy, and expanding green space.
3. Cities can convene key local stakeholders to advance voluntary actions in energy conservation, transit mode-shifting, impactful use of corporate social responsibility spending and climate mitigation.
4. Cities can coordinate technical assistance from relevant experts from cooperating international governments and multilateral lenders, local and international academic institutions, NGOs, multinational and peer-to-peer organizations (such as C40 and mayors' alliances).

National enabling policies are also needed to support clean air in cities

Cities in countries without strong clean air laws often face legal and practical limits on their ability to act locally, such as setting private fuel and vehicle emissions standards, limiting power plant emissions, and steering fuel choices toward cleaner and more renewable sources. While a majority of countries worldwide now have ambient air quality standards, progress towards achieving these standards is hindered not only by data gaps but also by limited monitoring and enforcement capacity, inadequate laws and regulations to control major sources, and political barriers to effective action (100). Lacking at present in many countries, for example, are modern standards for clean fuels and emissions from vehicles, power plants and industry, or the capacity to implement alternatives and controls on agricultural waste burning (101,102).

5.3 Organization for Action: Strategies and resources

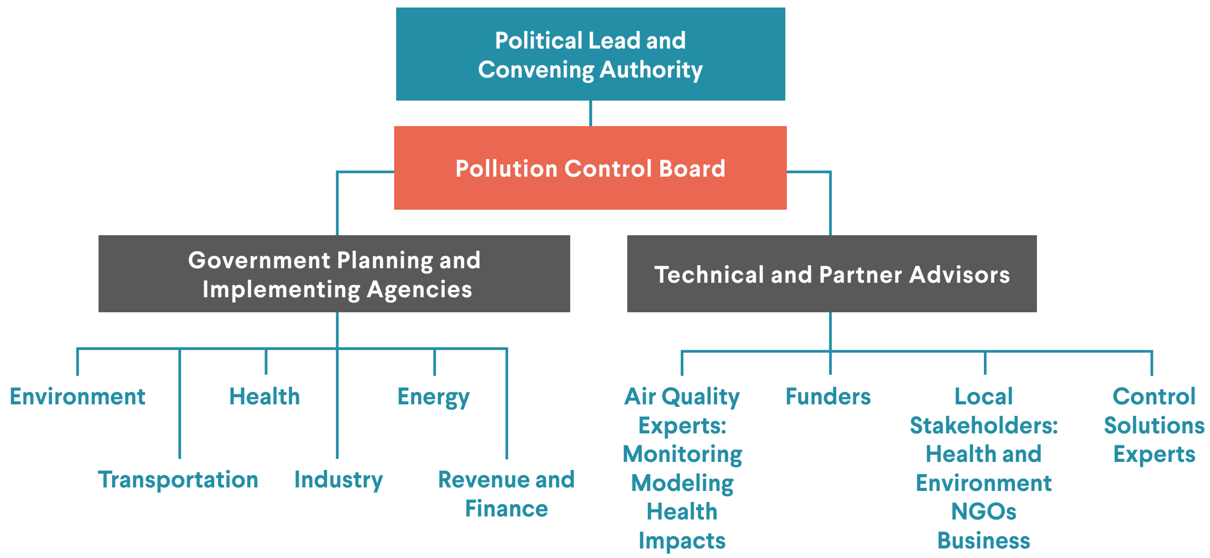
Cities can use their influence to help shape broader regional and national clean air policies. In addition to being hubs for civil society mobilization, cities can promote and participate in the establishment of regional air quality management planning and organizations or collaborate in advocacy with city partnership organizations.

Organized partnership among government entities, technical experts, civil society, the private sector, and others is needed to accelerate and sustain clean air action.

Cities should engage and coordinate the work of relevant agencies and partners in their efforts to improve air quality.

Technical partners and advisors, such as engineers, environmental scientists, economists, epidemiologists and others from local or international universities and research organizations can be invaluable in accelerating initial planning and action and building sustainable capacity that governments may lack in domains such as selection and siting of air pollution monitors, emissions modeling and source apportionment, health and economic impact modeling, multisectoral control solutions, and technology. Technical partnerships are most effective in building and sustaining capacity when they operate under a formal relationship with the government.

Figure 5b
Organizing multiple agencies and partners



Essential features include government executive leadership and convening function, representation and coordination roles among key government agencies and non-governmental partners. Depending on authorities in the local context, multiple levels of government (e.g. local, provincial, national) with mandate for regulation, enforcement, investment, and planning may be involved.

5.3 Organization for Action: Strategies and resources

Legal and policy advisors can also be valuable partners in designing clean air solutions. Cities and regions typically have greater authority to regulate local sources of emissions than they do for sources beyond their boundaries. Cities can engage their law offices, judicial branches and external academic legal experts to inventory and interpret relevant laws, as well as court and appellate decisions that enable cities' regulatory, legal, and fiscal policy opportunities. Experts can help devise creative solutions. For example, most cities can make science-informed choices about the purchase of vehicular fleets that are under municipal control, even if they cannot regulate emissions standards for private vehicles. In some countries, cities are able to choose to purchase government-used electricity from renewable fuel sources, even if they cannot prohibit the use of coal or other fossil fuels that affect their air quality.

Advocates and civil society organizations can be helpful and even essential for building the necessary constituencies to support action. Clinician associations and medical school faculty may help with public communication, framing health risks and benefits, and provide necessary advocacy for clean air policy proposals. Environmental and other civil advocacy organizations can offer support for improvements in monitoring and source identification, as well as government transparency. They can be encouraged to mobilize public support for clean air policies. Where authority exists outside of city or regional control, cities can engage advocates to socialize policymakers and the public to expect national action on their behalf. As discussed in Chapter 4, building a constructive relationship with civil society depends in part on sharing credible data and information on air quality, sources, health impacts and action plans.

Funding partners like philanthropists, donors and lenders can provide support for planning and technical assistance and can share lessons learned from other jurisdictions. National governments are more likely than cities to develop financing proposals for major capital improvements that can be leveraged for air quality improvements, but many international funding pools go untapped for lack of meaningful and impactful proposals. Cities should consider developing proposals to tap into World Bank, regional development banks, the Green Climate Fund, and venture capital to modernize fleets, improve mass transit, redesign streets, promote renewable and cleaner fuels, and build capacity within government for these activities.

While external funding can help catalyze initial planning and policy development, it is important to plan and budget for local, sustainable government resources for core air quality management functions, such as monitoring, inspections and enforcement. Experience has shown that relying solely on time-limited external grants and financing is unsustainable.

International organizations are also available to assist cities seeking to assess and control air pollution and build local capacity for sustained air quality management. These partnerships among cities serve as a mechanism for knowledge exchange or establishment of regional networks to address shared sources of trans-boundary pollution. Refer to Annex 7 for a list of some international organizations that provide additional technical assistance or convening support.

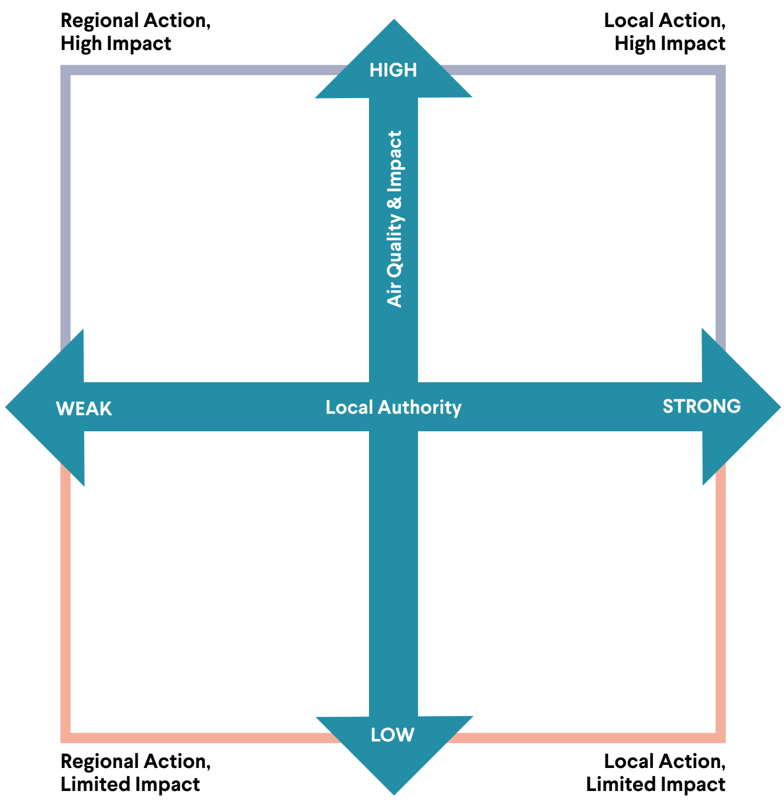
5.4
Developing and updating urban clean air action plans

The process of formalizing and publishing a clean air action plan should involve the participation of multisectoral governmental and nongovernmental stakeholders. The plan can take many forms—comprehensive or modular as components are completed; printed or online—but should evolve as more data become available and more polices are selected to address air pollutants. The objectives addressed by the plan should:

1. Confirm and document that air pollution levels are high enough to harm public health and that clean air actions are needed (refer to Chapter 2 on monitoring).
2. Assess and disclose local emissions and sources (refer to Chapter 3 on emissions and sources). Summarize available local emissions data.
3. Assess local control options, being mindful of legal and regulatory authority, estimated costs and other resource needs, opportunities and limitations.
4. Categorize local sources and control options and set priorities according to their potential impact on emissions, local authority, cost-effectiveness and feasibility. Figure 5c provides a suggested framework for this step. If feasible, model or use data, approaches and tools described in Chapter 3 to assess potential air quality impacts.
5. Identify and prioritize data limitations and improvement needs in areas including ambient monitoring, emissions and source assessment.
6. Assess capacity limitations and identify additional fiscal and human resource needs to control priorities and data.
7. Develop a near-term (two- to five-year), local clean air action plan, that includes:
   - Priority control measures, with agency responsibilities;
   - Data indicators of implementation progress;
   - Data improvement plans; and
   - Capacity building plans.
8. Develop a longer-term (five- to 20-year) and regional urban airshed, national action and policy agendas.

Figure 5c
Source control planning matrix

Classification of initial priorities for clean air action based on an assessment of emissions and sources contributing to ambient air pollution (Chapter 3) and local authorities (this chapter). Highest priority for near term actions are major local sources amenable to scalable, feasible controls (high air quality impact) that local government has authority to implement.



5.5
Conclusion:
Government's key role in accelerating clean air progress

Innovations, combined with conventional, proven air quality management approaches provide technical tools that make possible much faster progress towards clean air than was achieved in high-income countries during the past several decades. Frameworks for applying these technical tools have been described in Chapters 2, 3 and 4 of this guide.

Translating these technical tools into effective, rapid and sustained progress **requires political leadership** and a **commitment to advance the right to clean air** as well as effective and sustained organization, partnerships, planning and implementation.

City case studies of monitoring innovations in action:

New York City

Hong Kong

Beijing

Bangkok

Kathmandu Valley

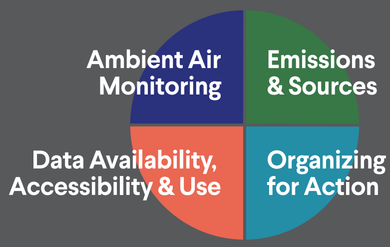
Battambang City

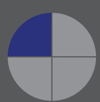
Accra

6

Case Studies

Summary of case studies in innovation



City	Innovations Applied	Actions
New York City, USA		Phase out high-sulfur heating oil
Hong Kong, China		Reduction of marine emissions
Beijing, China		Conversion of coal to natural gas
Bangkok, Thailand		Vehicle pollution control strategy
Kathmandu Valley, Nepal		Redesign brick kilns
Battambang City, Cambodia		Open waste burning mitigation
Accra, Ghana		Understanding contribution of a particular source of inform prioritization process
Oakland, USA		High-spatial-resolution mapping of air pollution in urban areas

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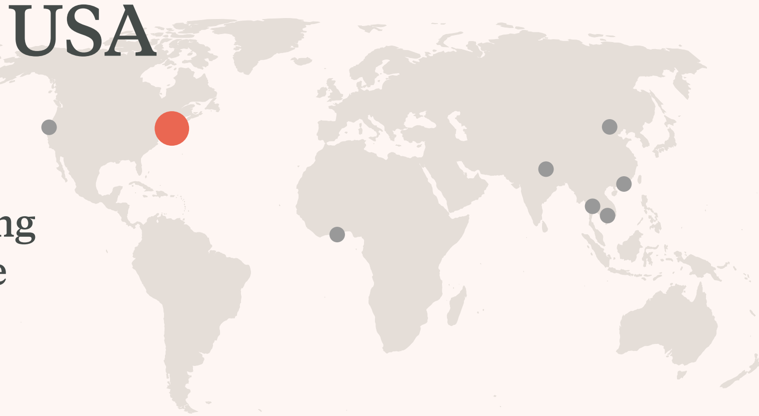
New York City, USA



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

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

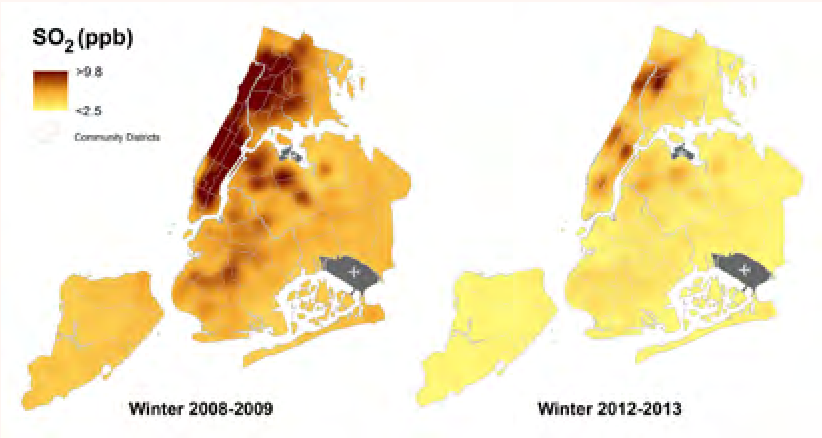
- **Government ministries**
  (e.g., NYC Department of Health)
- **Technical partners and advisors**
- **Legal and policy advisors**

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

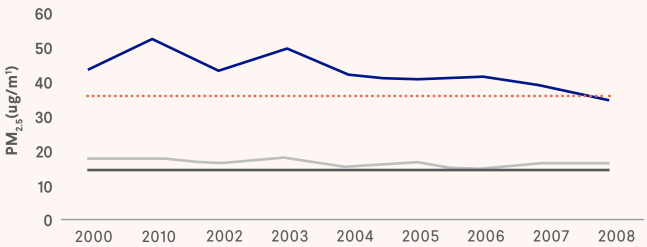
variation in air pollution across neighborhoods, identify important local sources and inform local clean air measures. NYCCAS deployed a spatially dense network of 100 to 150 integrated samplers—designed by a local university partner—to measure major pollutants. Data from the samplers were analyzed along 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 natural gas prices and a city program to assist

Exhaust from a boiler using high-sulfur heating oil.

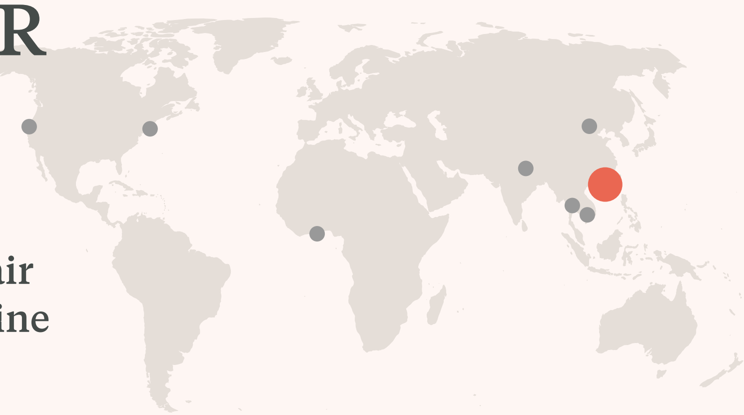
Source: https://www.nyccleanheat.org/content/problem
Photo Credit: Patti McConville

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.

Hong Kong, SAR



Experience on mitigation of air pollution emission from marine vessels

The Hong Kong Special Administrative Region (SAR) of the People's Republic of China is a subtropical coastal urban city in the boundary region of the Asian continent and Pacific Ocean, with a population of 7.4 million in 2018 (137). Hong Kong began its rapid economic and urban development in the 1960s, and has gradually transitioned from a manufacturing-based (e.g., textiles) economy to a service-based economy (138,139). Currently, the four main industries in Hong Kong are financial services, trading and logistics, tourism, and professional and producer services (140).

Primary stakeholders involved in Hong Kong's effort for air quality improvement

- **Government ministries** (e.g., Hong Kong Environmental Protection Department)
- **Private companies** (i.e., Fair Winds Charter)
- **Technical partners and advisors**
- **Advocates and civil society organizations** (e.g., Civic Exchange)
- **Regional government partners**
- **Legal and policy advisors**

The Issue

The Port of Hong Kong is a world-class international maritime hub that both serves the South Asian Pacific region and acts as an entrypoint for mainland China (141). In 2017, the port handled over 185,000 oceangoing and river vessels (142–144). It was estimated that the port would double its cargo-carrying capacity to 43 million 20-foot equivalent units (a unit of cargo capacity) by 2030 (145). However, these vessels were legally allowed to use high-sulfur bunker fuels (<4.5% sulfur) (146), which contribute to extremely high levels of ambient (SO_2) and (PM_{10}) (147,148). Shipping emissions have been shown to be responsible for 60,000 cardiopulmonary and lung cancer deaths worldwide and 14,500 to 37,500 premature deaths in East Asia each year (149,150). Given that about 3.8 million people risk direct exposure to marine air pollution because of the close proximity of the port to the Victoria Harbour and within several kilometers of the densely populated Kowloon Peninsula, shipping emissions pose a serious threat to public health (146,148).

Improved Emissions Inventory

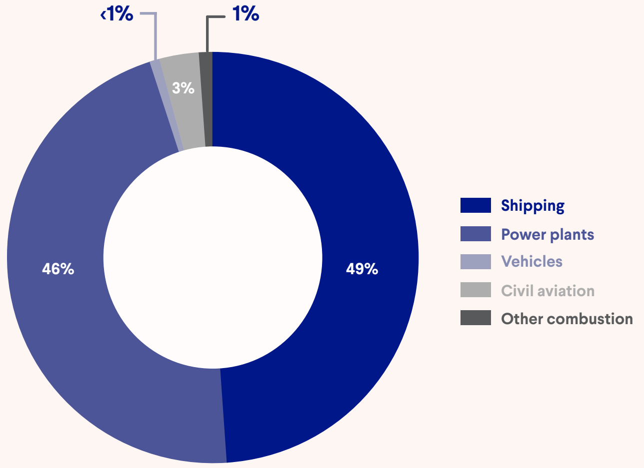
Hong Kong's primary effort to address its air pollution from shipping emissions was to refine its local marine vessels' emissions inventory. In 2000, the official air pollution emissions inventory showed that only 5% of the SO_2 emissions were from marine vessels (151). However, several source apportionment studies reported otherwise, that marine vessels were in fact the primary source of SO_2, suggesting severe underestimation of emissions from the shipping industry (151,152). One receptor-based source apportionment study showed that shipping emissions contributed to 36% of the ground-level SO_2 whereas only 7% was from power plants (151). Given the evidence, the official emissions inventory was revised using the improved local vessel activity data and latest emissions compilation methodologies (e.g., radar observations and ship information from the Automatic Information System) to provide more realistic estimates of shipping emissions (153). The revised emissions inventory showed that the contribution of marine vessels to SO_2 emissions had been increasing over the year, and it contributed to the latest emissions to SO_2 in Hong Kong in 2016 (154).

Organizing for Clean Air Actions

Another critical strategy was the strategic partnership and active engagement among key stakeholders on mitigation of shipping emissions in Hong Kong. One of the most notable initiatives was the Fair Winds Charter, an industry-led, voluntary, at-berth fuel switching program for oceangoing vessels calling at Hong Kong, which resulted in a discernible drop in ambient SO_2 concentrations near the port (155,156). The fuel switch benefits, along with support from civil society such as the Civic Exchange, prompted the Hong Kong government to roll out an incentive scheme and subsequently legislative bills in 2014 and 2015 on cleaner marine fuel and fuel switch at berth, respectively (157,158). Implementation of these measures resulted in immediate reduction of SO_2 and PM emissions from marine vessels, and a drop in the ambient concentrations of SO_2 and PM_{10} near the port in the following years (159).

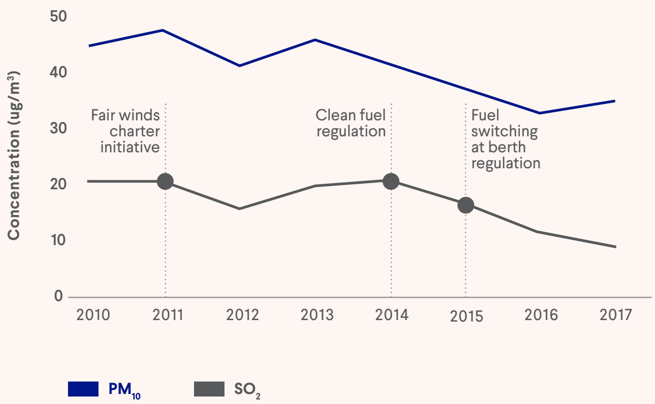
Furthermore, Hong Kong's experience in addressing shipping emissions sparked interest in the mainland of China. In an effort to tackle air pollution from shipping emissions from the neighboring Pearl River Delta region, and other major ports in China, the Ministry of Transport adopted a new policy to establish Domestic Emission Control Areas and introduce fuel switching that is similar to Hong Kong's oceangoing vessels fuel at berth regulation (160). Starting in 2019, all vessels plying within the Pearl River Delta's Domestic Emission Control Areas are required to run on low-sulfur fuel with the sulfur content not exceeding 0.5% (161).

Revised SO_2 emission inventory, 2016



Source: Ng SKW, Lin C, Chan J, Yip ACK, Lau AKH, Fung JCH. Study on Marine Vessels Emission Inventory.; 2012. https://www.epd.gov.hk/epd/sites/default/files/epd/english/environmentinhk/air/studyrpts/files/EPD_MVEIS_Final_Report_v7_approved_120528.pdf. Accessed September 5, 2019.

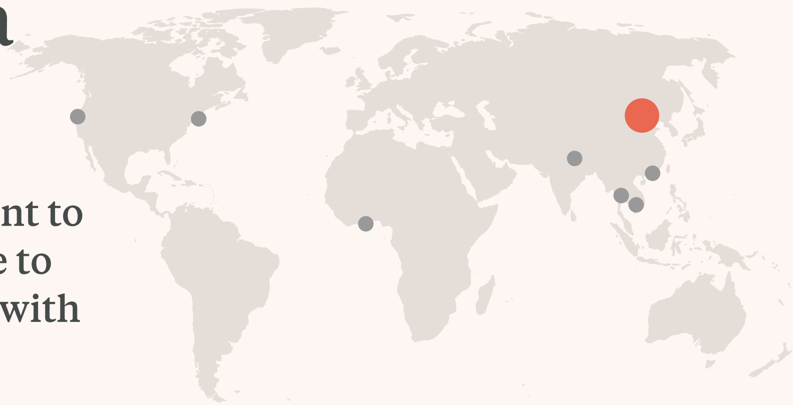
Annual ambient pollution concentrations near the port between 2010 and 2016



Lesson learned

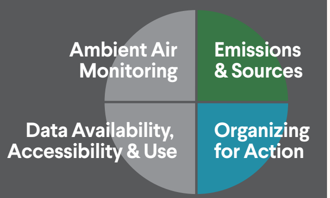
Hong Kong's experience in regulating and reducing emissions from marine vessels illustrates the importance of 1) evaluating and refining emissions inventory data, even in a high-income jurisdiction with a well-developed AQM system; 2) employing a combination of incentive and regulatory measures for air pollution control, suitable to the local context; 3) convening and engaging multiple local stakeholders in order to exchange and review evidence and knowledge, and align the awareness and interests of the key stakeholders for quick and smooth policymaking process; 4) acting both locally and regionally.

Beijing, China



Using source apportionment to inform a regional initiative to substitute residential coal with cleaner fuels

Innovations Applied



Beijing is the capital of the People's Republic of China, located in the northern part of the country. It is the second largest Chinese city, with a population of 21.7 million in 2017 (120). Beijing and two surrounding regions form the Beijing-Tianjin-Hebei metropolitan region, which is one of the prioritized mega city clusters in China, accounting for approximately 10% of China's gross domestic product (121,122). Beijing has a postindustrial economy that is heavily dominated by the tertiary sector (e.g., professional service, scientific research), and is home to the headquarters of most of China's state-owned enterprises, as well as many Fortune Global 500 companies (121).

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

- **Government ministries** (e.g., Ministry of Environmental Protection)
- **Regional government partners**
- **Technical partners and advisors**
- **Legal and policy advisors**

The Issue

Air pollution contributed to 1.2 million premature deaths in China in 2017, with even greater impacts on morbidity (123). The problem of air pollution is particularly severe in and around Beijing. The Beijing-Tianjin-Hebei region is among the most polluted in China, because of its heavy industry, reliance on coal and road-dominated transport. The annual concentration of $PM_{2.5}$ levels in the region was over 90 μg/m^3 in 2013 (124). Since 2005, the Chinese government has rolled out ambitious policy targets and emissions reduction programs with the specific focus on reducing coal burning for electricity production to improve ambient air quality. However, mitigation in the residential sector (i.e., household solid biomass and coal for cooking and heating) had been overlooked (125). As a result, severe haze events caused by $PM_{2.5}$, especially during the wintertime periods, have continued to occur.

Source Attribution

Source-based source apportionment studies in the past decade showed that the residential sector (i.e., household solid biomass and coal for cooking and heating) accounted for the largest percentage (~50%) of $PM_{2.5}$ levels in the Beijing-Tianjin-Hebei region during the heating season (123,126). It was estimated that over 177,000 premature deaths were attributed to household air pollution in China in 2017.

Organizing for Clean Air Actions

Given the mounting evidence of the contribution of residential sources during the heating season to ambient air quality, the National Development and Reform Commission and the National Energy Administration formu-

6

In 2017, air pollution caused **1.2 million premature deaths** in China; among that, ambient $PM_{2.5}$ pollution caused **over 850,000 deaths.**

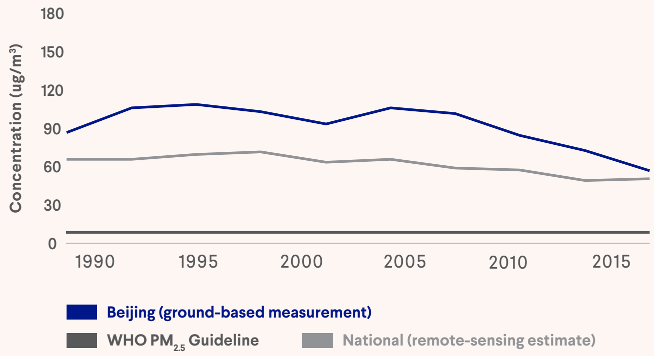
lated a campaign, "Clean winter heating plan for Northern China (2017-2021)," to substitute electricity or pipeline-based natural gas for heating in 70% of coal-using households within the 2+26 (i.e., Beijing, Tianjin, and 26 other municipalities in the surrounding area) region in northern China by 2021 (127).

In addition, the Chinese Ministry of Environmental Protection annually issues "Action Plan to Comprehensive Control Autumn and Winter Air Pollution in Beijing-Tianjin-Hebei and Surrounding Regions" to address residential emissions from coal use by substituting coal with natural gas and other clean fuels, controlling coal quality, promoting coal briquettes in rural areas, and monitoring the progress (125,128). As of October 2019, authorities had completed the replacement of small-scale residential coal burning in 5.24 million households (129). A recent study evaluating the potential impacts of the coal substitution campaign found that the campaign is generally effective in eliminating coal use and improving air pollution and life satisfaction in affluent households, and suggested that more subsidies and supports are needed to limit transitional hardships for less affluent households (130).

Lesson learned

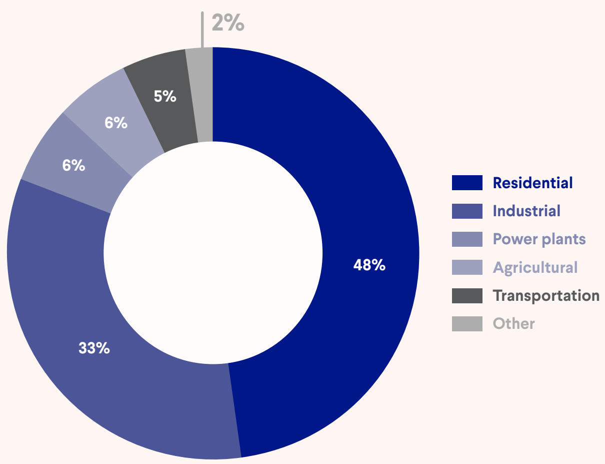
Beijing's experience demonstrates the value of using source apportionment with a regional airshed analysis along with identifying available, scalable interventions to prioritize clean air actions where they will have the greatest effect.

Trend of annual average ambient $PM_{2.5}$ concentrations in Beijing, and national compared to World Health Organization Air Quality Guideline



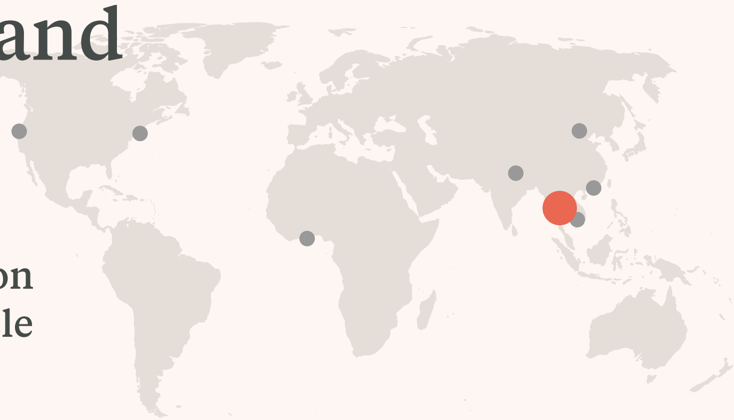
Source: The United States Department of State. AirNow. https://airnow.gov/index.cfm?action=airnow.global_summary. Accessed January 8, 2019; State of Global Air, available at https://www.stateofglobalair.org

$PM_{2.5}$ source apportionment results in Beijing-Tianjin-Hebei region, 2013 winter



Source: Li X, Zhang Q, Zhang 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;123:229-239. doi:10.1016/j.atmosenv.2015.10.048

Bangkok, Thailand



Tackling vehicular air pollution through comprehensive vehicle pollution control strategy

Bangkok is the capital city of Thailand, the third largest country in Southeast Asia in land area (109). Located in central Thailand along the Chao Phraya River, Bangkok is the most populous city in the country, with an estimated 8.28 million inhabitants in 2016, and over 14 million in its metropolitan region (110). The city is the economic center of Thailand, contributing to 29% of the gross domestic product (111). Wholesale and retail trade is the largest sector in the city's economy, followed by manufacturing, real estate, transport, communications and financial intermediation (112).

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

- **Government ministries**
  (e.g., Pollution Control Board, Bangkok Metropolitan Administration)
- **Legal and policy advisors**
- **Technical partners and advisors**

The Issue

Rapid urbanization in Bangkok started in the 1950s, leading to increased population density, as well as greater demand on infrastructure, public utilities and services. Despite the existing extensive road network, public transportation capacity was limited, leading to explosive growth of on-road private motor vehicles and motorcyles in the city, from 2 million in 1992 to over 9 million in 2016. Air pollutants emitted from motor vehicles using dirty fuels, coupled with dirty vehicles, have resulted in deteriorating air quality in Bangkok over the past several decades, with roadside PM_{10} levels of 90 μg/m^3 in 1997 (113). Elevated particulate pollution levels in Bangkok have been considered a significant risk factor of decreased lung function, increased respiratory symptoms, and cardiopulmonary hospital admissions (114,115).

Source Attribution

Local emissions inventory identified motor vehicles as the largest source (54%) of total PM emissions in the city. Among the vehicular PM emissions, 83% came from diesel engines (116). The significance of vehicular emissions to air pollution is also supported by findings from a study of receptor-based source apportionment, which shows large percentage of ambient PM_{10} and $PM_{2.5}$ concentrations contributing from motor vehicle exhaust emissions (117).

Organizing for Clean Air Actions

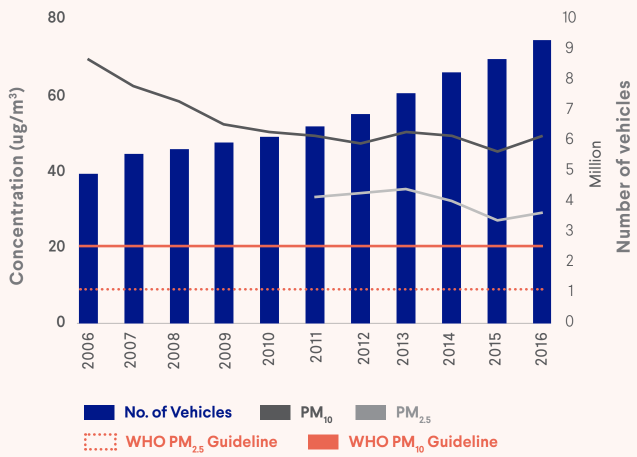
The Royal Thai Government has implemented a number of vehicle pollution control measures to mitigate Bangkok's air pollution problems, with an ultimate goal of lowering

In 2017, air pollution caused up to **30,600 premature deaths** in Thailand; ambient $PM_{2.5}$ pollution accounted for **78% of those deaths**

emissions and improving ambient air quality in line with the National Ambient Air Quality Standards or better (118). One of the important milestones was the complete phase-out of leaded gasoline at the end of 1995, which resulted in observed reduction in ambient lead levels and a significant decrease in blood lead levels in sensitive populations (e.g., school children and traffic police), particularly in urban areas, since the early 1990s (119). The adoption of cleaner fuel (e.g., phase-down of sulfur and phase-out of lead), and cleaner vehicle technologies (e.g., from pre-Euro to Euro IV, from two-stroke to four-stroke motorcycle engines), coupled with an enhanced vehicle inspection and maintenance program, are major contributing factors responsible for substantial improvement of ambient air quality in Bangkok (119). In addition, better transport and land use planning (e.g., development of the Mass Rapid Transit network in 2004) have played a role in reducing the dependence on motor vehicles, lowering pollution emissions and improving air quality (118). The annual average of PM_{10} concentration dropped from 90 μg/m^3 in 1997 to 49 μg/m^3 in 2016.

Lesson learned
Bangkok succeeded in improving urban air pollution from vehicular emissions. Success was informed by enhanced source identification, and comprehensive and synergistic vehicle pollution control strategies that target fuel quality, vehicle technologies and vehicle maintenance.

Trend of annual average ambient PM_{10} and $PM_{2.5}$ concentrations, and the number of vehicles registered in Bangkok between 2006 and 2016



Source: Pollution Control Department, Department of Land Transport (Transport Statistics Sub-Division, Planning Division) of the Bangkok Metropolitan Administration.

Kathmandu Valley, Nepal

Unique opportunity to rebuild brick kilns for cleaner air

Kathmandu Valley is located in the central region of Nepal, and it comprises Kathmandu, the capital city of Nepal, and the Lalitpur and Bhaktapur metropolitan areas, along with several other smaller cities and towns (162). The valley is home to 29% (~2.5 million) of the Nepalese urban population, and is one of the fastest-growing urban clusters in South Asia (163,164). The economic activities in Kathmandu Valley are mainly centered on the services sector, such as tourism, finance, trade, education and real estate (165).

Primary stakeholders involved in Kathmandu Valley's effort for air quality improvement

- **Regional government partners** (e.g., the International Centre for Integrated Mountain Development)
- **Private companies** (i.e., brick kiln owners)
- **Technical partners and advisors**
- **International organizations** (e.g., Climate and Clean Air Coalition)

The Issue

In Nepal, levels of $PM_{2.5}$ pollution are 10 times the WHO's recommended levels. About 12,700 Nepalese die prematurely from air pollution-related illness each year (105). The health costs due to urban air pollution in Nepal were estimated to be USD $21 million annually, and the actual economic burden could be substantially higher if taking into account the lost productivity from premature deaths or longer-term impacts from low birth weight, etc (166).

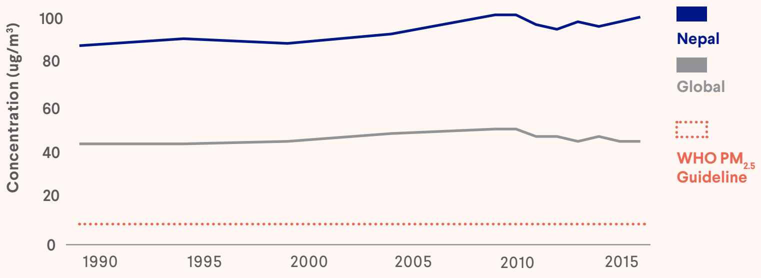
Brick is one of the most common building materials in Nepal, and brick making is one of the traditional crafts in Kathmandu Vally (167,168). Seasonally operated in winter (from Novermber to May), over 1,000 brick kilns in the country produce approximately 6 billion bricks each year, accounting for 2% of the bricks produced in Southeast Asia (169). Traditional brick kilns are considered one of the largest sources of air pollution in the valley. Coal is the main fuel for firing bricks in Nepal. Each year, brick kilns consume nearly 450,000 tons of coal, or ~ 30% of the total coal consumption in the industrial sector (170). A recent study found that brick kilns are the major source of black carbon (~40%) in Kathmandu Valley during winter (171). Besides excessive use of coal, the use of old-fashioned and inefficient brick firing technologies is also another primary reason for high air pollution emissions from brick industries (167). In Nepal, building kilns is often done on an ad-hoc basis. Not a single brick kiln in the country was constructed using engineered designs (172).

The Opportunity

A 7.8-magnitude earthquake struck central Nepal on April 25, 2015, causing catastropic harm to people and property across the country (173).

The country's brick industry also suffered a heavy blow, with over 40% (~350) of the kilns completely or partially destroyed and over USD $1 million in damages (172). Nearly all of the brick kilns in Kathmandu Valley were broken. Despite the devastation, a rare opportunity arose to rebuild the brick kilns with improved technology, and clean the polluted air in the valley.

Trend of annual average ambient $PM_{2.5}$ concentrations in Nepal and worldwide compared to World Health Organization Guideline



Source: State of Global Air, available at https://www.stateofglobalair.org

Organizing for Clean Air Actions

With support from the Climate and Clean Air Coalition, the International Centre for Integrated Mountain Development in collaboration with the Federation of Nepal Brick Industry and MinErgy explored ways to redesign the ovens and stack the bricks differently so that less polluted air is emitted (174). The initative carried out a feasibility study in 2017, which found that adopting the more efficient brick-kiln technology (i.e., zig-zag kilns) could reduce $PM_{2.5}$ emissions by ~20% and black carbon emissions by ~30% per kilogram of fuel (175).

Given that no proper guidelines on environmentally sound brick kiln construction were available in Nepal, a team of local brick entrepreneurs, engineers, scientists, architects and international experts developed a design manual in late 2015, with input from stakeholders in government, private sector, development organizations, NGOs, and media, to guide kiln owners and construction engineers to rebuild earthquake-resistant and more efficient induced draught and natural draught zig-zag kilns (174,176). The manual, the first of its kind in South Asia, takes into account energy efficiency, environmental concerns, and other social aspects, and serves as a basic tool to delineate the essential parameters for kiln construction. An operational manual was subsequently developed in 2016 to provide guidelines on proper stacking and firing procedures. Strategies and policy actions regarding the brick kiln industry were also recommended upon review of existing policy documents, and bilateral discussions with government stakeholders, consultation meetings with brick entrepreneurs, and sector experts (167).

While the cleaner brick kiln technologies require large upfront investment (~USD $100,000) from the kiln owners and entrepreneurs, as compared to old-fashioned technology, the payback period from fuel savings alone is expected to be less than two years, which is said to be a win-win situation for the industry, the environment as well as public health (172). This industry-led investment and buy-in resulted in rapid adoption of the cleaner technologies. In 2017, nine kilns were rebuilt using the new designs, and other kilns have adopted the brick stacking and firing techniques. This resulted in a 40% to 50% reduction in coal consumption by these kilns, as well as 60% reduction in PM emissions (172). At the same time, the number and quality of bricks produced also significantly increased due to the efficient moving of fire. As of May 2018, most of the 100 brick kilns in the Kathmandu Valley have already adopted the new cleaner technology (177).

Furthermore, Nepal's effort in redesigning brick kilns to zig-zag kilns and experience from progressive brick entrepreneurs in Kathmandu Valley attract much attention regionally. Numerous trainings for showcasing kilns were carried out, as well as exposure visits by entrepreneurs from other regions of Nepal, and India, Bangladesh and Pakistan. Given that there are over 130,000 brick kilns in South Asia, a Federation of Asia Brick Kiln Associations was formed to promote knowledge exchange and address multiple challenges through regional cooperation and collaboration (178).

Lesson learned

The experience in redesigning brick kilns in Kathmandu Valley showcases the importance of 1) seizing opportunities for industry rebuilding and new industry and infrastructure development to adopt less polluting and more efficient technologies; 2) the use of scientific data and engineered designs for design guidelines and policy recommendations; 3) the understanding the long-term benefits of adopting the cleaner technologies and designs that led to increased industry-led investment and buy-in; and 4) convening and engaging multiple local and regional stakeholders for knowledge exchange and raising awareness and interests to address the challenges.

Battambang City, Cambodia

Improving solid waste management for reduced emissions and multiple co-benefits

Battambang City is the capital of Battambang Province, a leading rice-producing province located west of Cambodia. With a population of nearly 200,000 in 2012, Battambang City is the third largest city of Cambodia, and a commercial hub and popular tourist destination (131,132). In general, levels of $PM_{2.5}$ pollution in Cambodia are two to three times the WHO recommended levels; nearly 11,000 Cambodians die prematurely from air pollution-related illness each year (105). Ozone concentrations in Cambodia are estimated to be typical for the SEA region (lower than the global average) but gradually increasing as the country develops.

Primary stakeholders involved in Battambang City's effort for air quality improvement

- **Government ministries** (e.g., Battambang City government)
- **Local non-government organizations** (e.g., Cambodian Education and Waste Management Organization)
- **International organizations** (e.g., Institute for Global Environmental Strategies, Climate and Clean Air Coalition)
- **Private companies and community members** (e.g., CINTRI)

The Issue

Battambang Municipality faces a range of challenges, such as poor sanitation, improper waste management, flooding and pollution, due to the lack of major infrastructure (131). The problem with solid waste management is especially concerning, because there is no consistent annual budget allocated to waste management services (133). Due to the deficiencies in solid waste management, open waste burning is a common way of disposing of waste (134). These burnings may be landfill fires, dumpsite burning, or residual open burning. Once a fire starts, it can continue for hours, or even months (in the case of landfill fires), causing air pollution and affecting waste pickers and residents of nearby communities.

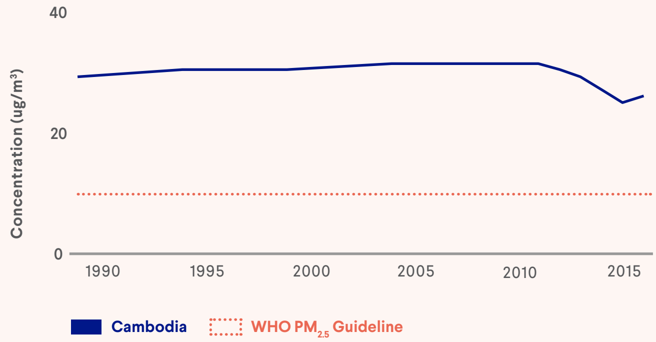
Solid waste burning releases a variety of toxic air pollutants (e.g., black carbon, benzene, carbon dioxide) that have been associated with severe cases of cardiorespiratory diseases and cancers among adults and children (135). Landfills can emit large amounts of methane, a potent greenhouse gas and ozone precursor.

Organizing for Clean Air Actions

With technical support from the Institute for Global Environmental Strategies and the Cambodian Education and Waste Management Organization, Battambang City launched a Participatory Waste Management Initiative in 2011 to set up community-based planning and implementation of climate-friendly waste management based on a 3R (reduction, reuse and recycle) approach, and to build capacity (133). Also, through this initiative, the Battambang government opened its doors to active participation and partnership from key

In 2017, air pollution caused **10,700 premature deaths** in Cambodia

Trend of annual average ambient $PM_{2.5}$ concentrations in Cambodia, and national compared to World Health Organization Air Quality Guideline



stakeholders (i.e., local nongovernment organizations, private companies and community members) in the areas of project planning, decision-making, implementation, and monitoring and evaluation. Key activities implemented in the initiative include (133):

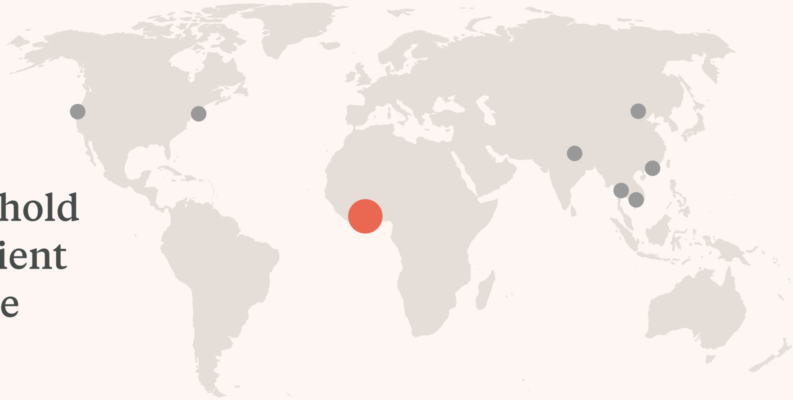
1. **City-to-city training program:** On-site intensive training was carried out by the Phitsanulok municipality from Northern Thailand to share their successful experience in overcoming their waste management challenges, and how the community-based approach to waste management can succeed in Battambang. Waste management strategy drafted during the training was adopted, and a local regulation for waste separation at source was also developed in support of the strategy, and introduced in several pilot areas around the city.
2. **Promote source separation and collection:** Given that nearly three-fourths of the municipal waste is organic and there was a preexisting composting facility in Battambang city available, priority was set for separation, collection and compositing of organic waste.
3. **Manage landfill fires:** Training on fire extinguishing was conducted among site operators, waste pickers and farmers around the dumpsite; in addition, campaigns were carried out to promote waste separation to reduce waste volume.
4. **Combat open waste burning and littering:** Residents in Battambang City on average burn approximately two metric tons of waste each day due to poor waste collection services. To address this issue, several interventions were implemented to prohibit open burning and littering, to improve collection and supporting services and to conduct regular cleaning and awareness campaigns.

This effort was further expanded when Battambang Municipality joined the Municipal Solid Waste Initiative of the Climate and Clean Air Coalition in 2014—the first Cambodian city to do so—and received technical support to conduct assessment of short-lived climate pollutants emissions from the waste sector (136). In 2017, Battambang Municipality was the first Cambodian city to draft a local waste management regulation as a legal tool to translate the national Sub-Decree 113 on *Urban Solid Waste Management* into local contexts in terms of action plan and implementation.

Lesson learned

The example of open waste burning mitigation in Battambang City shows that 1) certain sectors (waste management in this case) are low-hanging fruit for cities to start tackling for air pollution emissions reduction; 2) community-based approaches through convening and engaging multiple local and regional stakeholders for knowledge exchange and awareness raising are critical to address the challenges.

Accra, Ghana



Understanding how household energy contributes to ambient air quality to help prioritize clean air action

Accra is the capital and largest city of Ghana. Located at the southernmost tip of Ghana, the city is home to an estimated 2.3 million urban residents (2015) (103). Rapid in-migration, both from the countryside and from other West African nations, has brought a series of transformations to Accra's urban economy (104). Accra is a major center for manufacturing and financial sectors, as well as the service sector and fishing industry.

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

- **Government ministries** (e.g., Ghana Environmental Protection Agency)
- **Technical partners and advisors** (i.e., Health Effects Institute)

The Issue

In Ghana, 73% of the population still uses solid fuels and kerosene to meet their household energy needs, resulting in household air pollution and contributing to nearly 10,000 premature deaths in 2017 (105). The Ghana Environmental Protection Agency and Stockholm Environment Institute estimated that 65% of the total national primary $PM_{2.5}$ emissions in Ghana in 2010 were attributable to residential, or indoor, sources (e.g., household cooking, lighting and heating) (106). However, uncertainty remains about the extent to which household air pollution (air pollution indoors and around the home from household fuels) contributes to ambient air pollution in Ghana. In 2018, the Greater Accra region adopted a draft Air Quality Management Plan to address ambient, or outdoor, air pollution; however, the plan does not include specific action items on household air pollution.

Source Attribution

Local receptor-based source apportionment studies reported biomass burning as an important contributor to ambient $PM_{2.5}$ concentratons in Accra. On average, 36% (ranging from 15% to 42%) of the ambient $PM_{2.5}$ was attributed to biomass burning (related to biomass as fuel for cooking, heating and/or open burning) in Accra (107). However, results from such studies are locally specific, and estimates from biomass burning contributions are not specific to household use of solid fuels, but may include other forms of biomass burning such as open burning or commercial activities (106).

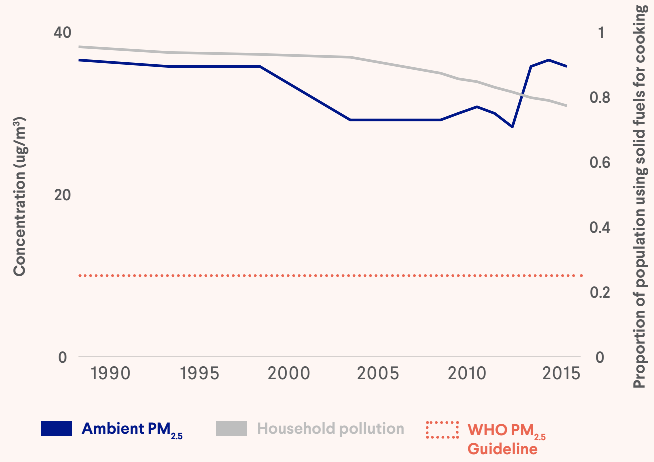
To complement the findings from receptor-based source apportionment studies, several source-based assessments of $PM_{2.5}$ emissions were used to delineate residential emissions in Ghana at the

In 2017, air pollution caused **15,100 premature deaths** in Ghana; among that, household air pollution from solid fuels caused **9,780 deaths.**

current state and for various future scenarios. These studies not only found significant contrbution of primary $PM_{2.5}$ emissions from residential fuel use, but also enabled mapping those contributions at the local level throughout Ghana, especially Accra (106). Preliminary work from the Urban Emissions research group (www.urbanemission.info) suggests substantially higher emissions rates for cooking-related PM in the major urban areas (108).

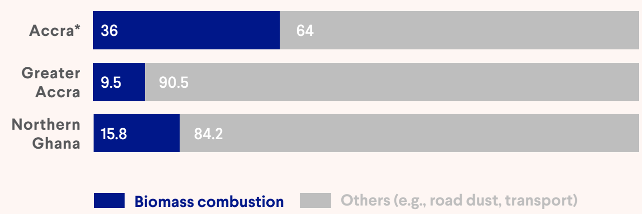
Lesson learned
Local source apportionment studies and enhanced emissions inventories with a special focus on the contribution of household energy were used to make the case for addressing a leading source of pollution across Ghana, especially for expanding access and use of clean household energy for cleaner outdoor air. Ghana Environmental Protection Agency has since been undertaking a bigger program to set up facilities to conduct top-down source apportionment studies.

Trend of ambient $PM_{2.5}$ concentrations and household air pollution in Ghana compared to World Health Organization Air Quality Guideline



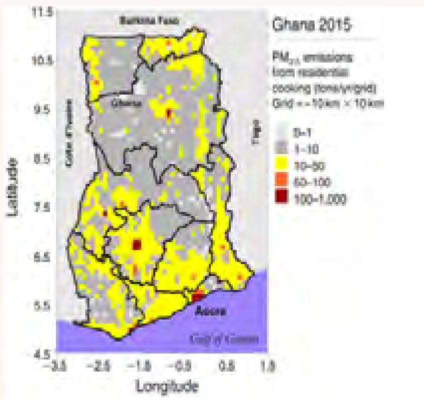
Source: State of Global Air, available at https://www.stateofglobalair.org

Percentage contribution to ambient $PM_{2.5}$ concentration based on top-down source apportionment studies



Source: HEI Communication 19: Contribution of Household Air Pollution to Ambient Air Pollution in Ghana: Using Available Evidence to Prioritize Future Action, 2019, available at https://www.healtheffects.org/system/files/Comm19-HAP-Ghana.pdf

Spatial distribution of primary $PM_{2.5}$ emissions from residential cooking in Ghana, 2015

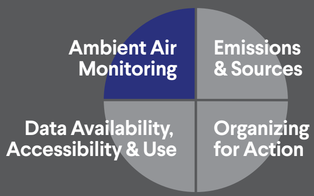


Source: HEI Communication 19: Contribution of Household Air Pollution to Ambient Air Pollution in Ghana: Using Available Evidence to Prioritize Future Action, 2019, available at https://www.healtheffects.org/system/files/Comm19-HAP-Ghana.pdf

Oakland, California, USA

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

Innovations Applied



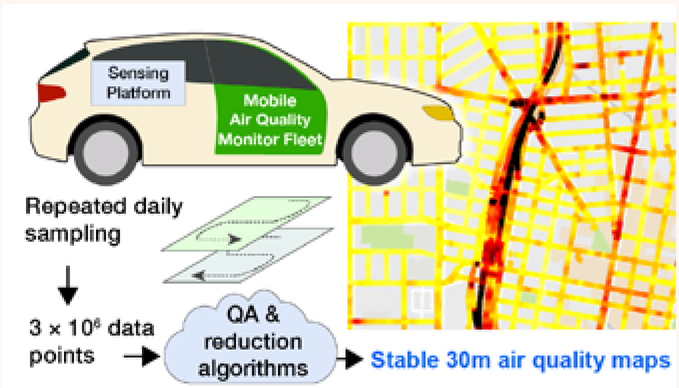
The city of Oakland is one of the most populated cities in California, with 431,000 residents in 2018 (193). Once known for its harbor and deep-water port, Oakland now has a highly diversified economy and is home to several major corporations (194,195). The major industries in Oakland as measured by 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/

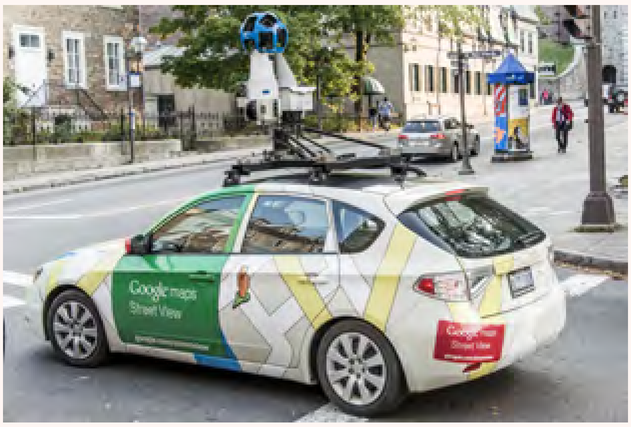
Enhanced Ambient Air Monitoring

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.

A

Annexes

A

Annex 1
Online data sources on air pollution's global health burden

State of the Global Air - https://www.stateofglobalair.org/data/
The State of the Global Air (SOGA) reports on global, regional, and country-specific data on air quality and health. In addition to their annual report, national air quality and health burden data are available in plots, maps, and tables for ambient PM, ozone, household pollution, deaths and DALYs (disability-adjusted life years).

GBD Compare - https://vizhub.healthdata.org/gbd-compare/
GBD (Global Burden of Disease) Compare is a highly interactive visualization tool developed by the Institute for Health Metrics and Evaluation (IHME). Use this tool to explore and compare the different health risks and disease burdens imposed by air pollution within and between demographics, countries, and regions.

WHO Global Health Observatory - http://www.who.int/gho/phe/en/
The World Health Organization's (WHO) health observatory database details health statistics for over 1000 health-related indicators of progress towards achieving the Sustainable Development Goals (SDGs) for 194 WHO member states.

Map Gallery - http://gamapserver.who.int/mapLibrary/app/searchResults.aspx
Search the map gallery to see how health burdens of air pollution in your country compares to others. Start by searching "air pollution" in keywords or selecting the "Environment and Health" Topic.

Outdoor air pollution death and disease burden - http://www.who.int/gho/phe/outdoor_air_pollution/burden/en/
Explore the mortality rates and disease burdens of outdoor air pollution of countries using this interactive map and plot.

Outdoor Air Pollution Data Repository – Burden of Disease - http://apps.who.int/gho/data/node.main.BODAMBIENTAIR?lang=en
Explore and download burden of disease data repository for outdoor air pollution in terms of deaths, DALYs (disability-adjusted life years), and YLLs (years of life lost).

Household air pollution death and disease burden - http://www.who.int/gho/phe/indoor_air_pollution/burden/en/
Explore the mortality rates and disease burdens of household air pollution of countries using this interactive map and plot.

Household Air Pollution Data Repository – Burden of Disease - http://apps.who.int/gho/data/node.main.139?lang=en
Explore and download burden of disease data repository for outdoor air pollution in terms of deaths and DALYs.

Joint Effects of Air Pollution Data Repository - http://apps.who.int/gho/data/node.main.ENVHEALTHJOINTAAPHAP?lang=en
Explore and download the combined mortality data for outdoor and household air pollution by country or region.

WHO World Health Statistics Annual Report - http://apps.who.int/iris/bitstream/handle/10665/272596/9789241565585-eng.pdf?ua=1
The World Health Organization (WHO) provides an annual report of health statistics for WHO member states monitoring health for the Sustainable Development Goals (SDGs). The 2018 annual report's section on Mortality Due to Air Pollution (pg 39) shows the mortality rate attributed to household and ambient air pollution in each country.

Annex 2
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.

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Annex 2
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.

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.

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Annex 2 | 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 3
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	Required and consistently performed	Required and consistently performed	Encouraged, but new techniques needed
Traceability to the primary standard via direct comparison	Required and consistently performed	Required and consistently performed	Common practice but not consistently occurring
Best practices for measurement guidelines and SOPs	Required and consistently performed	Required and consistently performed	Encouraged, but new techniques needed
Use of data quality objectives (e.g. precision, accuracy, stability, drift) for an application	Required and consistently performed	Required and consistently performed	Common practice but not consistently occurring
Onsite maintenance	Required and consistently performed	Required and consistently performed	Common practice but not consistently occurring
Implementation of the QA (e.g. calibration, validation) procedures	Required and consistently performed	Required and consistently performed	Common practice but not consistently occurring
Comparison among instruments/sensors in the network	Required and consistently performed	Required and consistently performed	Encouraged, but new techniques needed
Independent site and instrument audits	Required and consistently performed	Required and consistently performed	Encouraged, but new techniques needed
Open/transparent data processing algorithms	Common practice but not consistently occurring	Common practice but not consistently occurring	Common practice but not consistently occurring
Open data sharing	Required and consistently performed	Required and consistently performed	Common practice but not consistently occurring
Site and instrument operation log	Required and consistently performed	Required and consistently performed	Encouraged, but new techniques needed
In-depth training available	Required and consistently performed	Required and consistently performed	Encouraged, but new techniques needed

Source: World Meteorological Organization

- Required and consistently performed
- Common practice but not consistently occurring
- Encouraged, but new techniques needed

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Annex 4
Comparison Source-Based and Receptor-Based Source Apportionment

	Source-based "bottom-up" approach	Receptor-based "top-down" approach
Description	In this approach an emissions inventory is established for all the known source sectors and analyzed with atmospheric models to estimate the contribution of each source to ambient pollution and composition across a geographic area.	In this approach, ambient samples are analyzed for chemical composition and compared with chemical profiles of emissions from different fuels. A statistical model is used to estimate the share of each fuel's contribution to the measured ambient sample.
"Source" definition	Typically, "source" refers to a sector and in some cases, it can refer to a region.	Typically, "source" refers to the type of fuel and with some assumptions it can refer to a sector.
Major limitations	The quality and detail of emissions inventory data depends on the accuracy of emission factors, which can vary by region and combustion technologies, the accuracy of fuel consumption data and of relevant activity data such as vehicle miles driven.	It is difficult to separate contributions from sectors burning the same fuels. For example, chemical profiles are similar among diesel generators, trucks and construction equipment; between dust from wind erosion and dust resuspended from road traffic; and between biomass burnt in an open field and inside homes for cooking.
Spatial representativeness	Analysis results are representative of the entire airshed selected for the emissions and the chemical transport modelling exercise.	Analysis results are representative of the locations where samples are collected and locations similar in terms of source impacts, for an individual monitor. The representativeness of the overall result to a city or a region depends on the number and representativeness of sampling locations compared to the city or the region.
Temporal representativeness	Analysis results will be available at various temporal scales – by hour, by day, by month, and by season, depending on the temporal resolution of the emissions data and the chemical transport modelling exercise. For planning, future source impacts can be estimated for various emission scenarios.	Analysis results are representative of the time period during which a sample is collected. Because of this, multiple samples are required by month and season to ascertain the temporal trends in source contributions during a given time period. Not suitable for estimating future scenario sector contributions.

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Annex 4
Comparison Source-Based and Receptor-Based Source Apportionment (cont.)

	Source-based "bottom-up" approach	Receptor-based "top-down" approach
Cost	VARIABLE – depending on the primary data collection required, modelling tools employed, and granularity of the emissions and chemical transport modelling exercise. Some emissions and activity data may be collected for other purposes (e.g. fuel tax revenues, traffic management) and available for little or no cost.	HIGH – Samplers, lab equipment for chemical analysis, and other logistics like travel to and from the sampling locations, and staff time is HIGH. Overall total cost depends on the number of sampling locations in the airshed and number of samples collected per season.
Laboratory needs	VARIABLE – only when primary data collection is carried to ascertain the emission factors by fuel and by sector.	HIGH – a stringent set of protocols must be followed starting from sampling, storage, chemical analysis, source profiling, QAQC, and receptor modelling.
Personnel needs	LOW to MEDIUM – Once emissions and meteorology data are assembled; several modeling exercises can be implemented covering multiple scenarios and time periods across an entire region or urban airshed.	HIGH – Includes personnel to perform field, laboratory and statistical modeling tasks as described below. Advanced, semi-autonomous samplers can reduce personnel time in the field.
Personnel skill needs	HIGH – experienced staff is required to collate/manage/map/analyze the emissions inventory for the airshed; experienced staff is required to operate/calibrate/analyze the meteorology coupled chemical transport models for the airshed to ascertain the source contributions	HIGH – experienced staff is required to collect/store/record the samples during the field experiment; experienced staff is required to operate/calibrate/analyze the samples in the lab; and experienced staff is required to conduct the receptor modelling exercise involving selection and use of relevant source profiles.
Computational needs	HIGH – depending on the chemical transport model of choice, chemical mechanism selected, spatial and temporal resolution of the modelling system, and range of output parameters, computational needs can range from HIGH to VERY HIGH	MINIMUM – statistical receptor modelling packages can be run on a personal computer.
Time needed to complete a study	Typically, less than one year for studies covering multiple scenarios including prospective projections.	Typically – one year for the sample exercises and 1-2 years for chemical analysis and receptor modelling (depending lab capacity). Each analysis applies to a retrospective cross-section of time.

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Annex 5 | Table 1
Emissions and source apportionment resources
List of global anthropogenic emission inventories

Resource	Website	Geographic resolution, coverage, data period, and sectors included	Brief description	Comments, strengths, limitations
Global Inventories (all species considered)				
HTAPv2.2 (Hemi-spheric Transport of Air Pollution)	Documentation: **https://www.atmos-chem-phys.net/15/11411/2015/acp-15-11411-2015.pdf** Data: **http://edgar.jrc.ec.europa.eu/htap_v2/**	• Global, regional (e.g., USA, Europe, China, Africa) • 0.1° grid size • Years 2008 and 2010 • *Anthropogenic:* 7 sectors (i.e., power, industry, residential, agriculture, ground transport, aviation and shipping)	The HTAPv2 is a compilation of officially accepted regional and national gridded emission inventories and complemented with EDGARv4.3 grid maps for countries or sectors without reported data.	Strengths • A harmonized emission data set with global coverage and high spatial resolution • Collection of official inventories • Recommended as a global baseline emission inventory Limitations • Emission excludes large-scale biomass burning (forest fires, peat fires and their decay) and agricultural waste or field burning. • Inconsistencies at the country borders between two adjacent inventories, yielding high emission variation at cross border grids
EDGARv4.3.2 (Emis-sions Database for Global Atmospheric Research)	Documentation: **https://www.earth-syst-sci-data.net/10/1987/2018/essd-10-1987-2018.pdf** Data: **http://edgar.jrc.ec.europa.eu/overview.php?v=432**	• Global, regional, country-specified • 0.1° grid size • 1970 – 2012 (up to 2017 for fossil CO2 emissions) • *Anthropogenic:* 5 main emission categories (i.e., energy, industry and processes, transport, residential, and agriculture) and 32 aggregated emission subsectors	The EDGAR v4.3.2 dataset provides global past and present day anthropogenic emissions of greenhouse gases and air pollutants based on publicly available statistics. **Version 5:** CO2 **Version 4.3.2:** GHG (CO2, CH4, N2O) and AP (gases and aerosols), VOS and NMVOC	Strengths • Consistent bottom-up emission calculation methodology applied for all world countries in a sectorial structure • Allow comparison of country- and sector-specific sources Limitations • No emission for BC and OC • Less accurate information at subnational or urban focus • Lack detailed modeling of subsector emissions
ACCMIP (Atmospheric Chemistry and Climate Model Intercomparison Project)	Documentations: **https://www.atmos-chem-phys.net/10/7017/2010/acp-10-7017-2010.pdf** **https://www.giss.nasa.gov/projects/accmip/** Data: **https://eccad3.sedoo.fr/**	• Global and regional estimates • 0.5° grid size • 1850 – 2100 • *Anthropogenic:* 8 sectors (i.e., transportation, energy, industries, residential, solvents, agriculture, agricultural waste, waste) • Biomass burning: 2 sectors (savanna burning and forest fires)	ACCMIP is a dataset of sectoral, gridded anthropogenic and biomass burning emissions with 2000 as the point for historical emissions (from 1850 – 2000) and future emissions (up to 2100). It was developed together with the emissions projections of the RCPs, and for use needed by CMIP5 in support of the IPCC Assessment Report 5 report.	Strengths • Provide consistent gridded emissions of reactive gases and aerosols for use in chemistry model simulations needed by climate models for CMIP5. Limitations • Lack of full consistency between CO2, reactive gases and aerosol emission due to the use of a variety of inventories. • Cannot reproduce interannual variability due to the focus on long-term changes. • Underestimation of the long-term trends in surface and mid-troposphere ozone.
RCPs (Representative Concentration Pathways)	Documentation: **http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html** Data: **http://www.iiasa.ac.at/web-apps/tnt/RcpDb**	• Global and regional estimates • 0.5° grid size • 2000 – 2300 • *Anthropogenic:* 9 sectors (i.e., transportation, energy, industries, ships, residential, solvents, agriculture, agricultural waste, waste) • Biomass burning: 2 sectors (savanna burning and forest fires)	The RCP database contains projections of future emissions based on different radiative forcing levels (i.e., RCP 2.6 or 3PD, 4.5, 6.0 and 8.5), and is generated by Integrated Assessment Models, which uses the 2000 emissions as an anchor point. The projections are extended for climate modeling experiments to 2300.	Strengths • The RCPs are compatible with the full range of stabilization, mitigation, and baseline emission scenarios available in the current scientific literature. Limitations • The RCPs are neither forecasts nor policy recommendations. • The four RCPs together cannot be treated as a set with consistent internal socioeconomic logic.

Resource	Website	Geographic resolution, coverage, data period, and sectors included	Brief description	Comments, strengths, limitations
MACCity (MACC/CityZEN EU projects)	Documentations: **http://hdl.handle.net/10.1007/s10584-011-0154-1** **https://www.atmos-chem-phys.net/6/3423/2006/acp-6-3423-2006.pdf** Data: **https://eccad3.sedoo.fr/**	• Global and regional estimates • 0.5° grid size • 1960 – 2010 • *Anthropogenic:* 9 sectors (i.e., transportation, energy, industries, ships, residential, solvents, agriculture, agricultural waste, waste) • Biomass burning: 2 sectors (savanna burning, forest fires)	MACCity, developed as part of MACC and CityZen projects, is new inventory of global anthropogenic emissions, which provides up-to-date estimates for use in the global MACC models. The biomass burning emissions dataset (based on RETRO and GFEDv2; 1960 – 2008).	**Strengths** • The inventory is an extension of decadal ACCMIP (for CMIP5) and RCP 8.5 emissions to annual values with a seasonal cycle (based on RETRO). **Limitations** • Inaccuracy due to a potential source of error common to long term chemistry climate simulations of tropospheric species and their impact on radiative forcing.
HYDE1.3 (or EDGAR-HYDE; Hundred Year Database for Integrated Environmental Assessment)	Documentation: **https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2000GB001265** Data: **https://themasites.pbl.nl/tridion/en/themasites/edgar/emission_data/edgar-hyde-100yr/edgar-hyde-1-3-gridded-emissions.html**	• Global, regional and country-based estimates • 1° grid size • 1980 – 1990 • *Anthropogenic:* 5 sectors [i.e., energy use, industrial processes, agriculture (non-burning), biomass burning, agricultural waste burning and landfills]	An anthropogenic emissions data set is constructed for CO2, CO, CH4, nonmethane volatile organic compounds (NMVOC), SO_2, NOx, N2O, and NH3 using an emission factor approach. The inventory is based on the emission factors for uncontrolled sources in EDGARv2.0 for 1990.	**Strengths** • Greenhouse and reactive trace gas emission estimates are calculated consistently using the EDGAR system so that future improvements concerning activities and emission factors can be easily implemented. **Limitations** • Significant uncertainties especially for historic emissions • Unclear distinction between anthropogenic and natural sources • Neglected secondary effects of human activities on natural sources such as methane emissions from wetland changes
RETRO (Reanalysis of the TROpospheric chemical composition)	Documentation: **http://gains.iiasa.ac.at** **https://www.sciencedirect.com/science/article/pii/S1364815211001733** **https://www.atmos-chem-phys.net/15/10529/2015/acp-15-10529-2015.pdf** Data: **http://www.iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv5.html** **http://gains.iiasa.ac.at/gains**	• Global, regional and country-based estimates • 0.5° grid size • 1990 – 2050 • *Anthropogenic:* 8 sectors (i.e., transportation, energy, industries, residential, solvents, agriculture, agricultural waste, waste)	The ECLIPSE dataset is an inventory for past and future anthropogenic SLCP emissions, and their spatial distribution. It was created with the GAINS (Greenhouse gas – Air pollution Interactions and Synergies) model, which calculates emissions of air pollutants and Kyoto greenhouse gases in a consistent framework. The GAINS model holds essential information about key sources of emissions, environmental policies, and further mitigation opportunities for 172 country regions.	**Strengths** • Inventory is updated to current legislation for the recent past and until 2050 • Detailed comparisons between measured and modelled distributions of aerosol, O3 and other SLCP gases have shown that for many substances the models are in good agreement with available background observations **Limitations** • The inventory does not include international shipping and aviation, nor independent estimates of emissions from forest fires and savannah burning, windblown dust, and unpaved roads
CEDS (Community Emission Data System)	Documentation: **https://www.geosci-model-dev.net/11/369/2018/** **https://www3.epa.gov/ttn/chief/conference/ei21/session2/ssmith.pdf** **http://www.globalchange.umd.edu/ceds/** Data: **https://esgf-node.ipsl.upmc.fr/search/esgf-ipsl/**	• Global, regional and country-based estimates • 0.5° grid size • 1750 – 2014 • *Anthropogenic:* 8 sectors (i.e., transportation, energy, industrial process, ships, residential, solvents, agriculture, waste)	CEDS uses existing emissions inventories, emissions factors, and activity/driver data to estimate annual country, sector, and fuel specific emissions over time for use in the CMIP6 model. Emission estimates are developed using IEA energy statistics and emissions factors, mostly derived from GAINS (combustion), EDGARv4.3 (non-combustion) and CDIAC (for CO2 emissions).	**Strengths** • Combine existing emissions estimates with driver data (e.g., fuel use) for consistent estimates of emissions over time. • Uncertainty estimated for all emissions as part of the output of the system. **Limitations** • Emission trends for key non-combustion sectors are less accurate, particularly for years where country-level emission data sets are not available. • Lack of consistently constructed spatial gridding proxies over time.
CAMS-GLOBAL (Copernicus Atmosphere Monitoring Service)	Documentations: **https://atmosphere.copernicus.eu/sites/default/files/2018-05/CAMS81_2017SC1_D81.2.2.2-201802_v3_APPROVED_Ver3.pdf** Data: **https://atmosphere.copernicus.eu/anthropogenic-and-natural-emissions**	• Global, and European estimates • 0.1° grid size 2000 – 2020 • *Anthropogenic:* 11 sectors (i.e., ships, fugitives, power generation, off-road and road transportation, industrial process, residential, solvents, agriculture, agriculture livestock, solid waste and waste water) • Additional global inventories for ship, oceanic, soil, biogenic, termites, volcanic, aviation	CAMS provides daily-monthly gridded distributions of European and global anthropogenic emissions, as well as global natural emissions. CAMS emissions are based on various existing data sets (e.g. nationally reported emissions, EDGAR, ECLIPSE, CEDS, POET), which ensures good consistency between the emissions of greenhouse gases, reactive gases and aerosol particles and their precursors. It is built on work being done in MACC, -II and –III projects.	**Strengths** • Based on more realistic data reported at the country level and more realistic, detailed seasonal profiles

Resource	Website	Geographic resolution, coverage, data period, and sectors included	Brief description	Comments, strengths, limitations
POET (Precursors of Ozone and their Effects in the Troposphere)	Documentation: **http://accent.aero.jussieu.fr/Documents/POET_documentation.pdf** Data: **http://www.aeris-data.fr/redirect/POET** **http://accent.aero.jussieu.fr/database_table_inventories.php**	• Country and sectoral estimates • 1° grid size • 1990 – 2000 • *Anthropogenic:* 14 sectors (e.g., industry, power generation, transport road, cement, waste) • Biomass burning: 2 sectors (savanna burning, forest fires)	POET is global emissions of gases (ozone precursors) from anthropogenic, natural, and biomass burning sources have been estimated for the period 1990-2000. The POET anthropogenic, biomass burning, biofuel and agricultural waste emissions are based on EDGAR v3.2 emissions.	**Strengths** • Scenarios of the evolution of ozone precursors, which are not included in the IPCC studies, were developed to take into account emission reduction policies that are consistent with European or international agreements. **Limitations** • Inherent uncertainty due to modeled, rather than measured, estimates

Global Inventories (selected number of species)

Resource	Website	Geographic resolution, coverage, data period, and sectors included	Brief description	Comments, strengths, limitations
BOND or SPEW v5.6 (Speciated Pollutant Emission Wizard; BC and OC)	Documentation: **https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2006GB002840** Data: **http://www.hiwater.org/**	• Country and sectoral estimates • 1° grid size • 1850 – 2000 • *Anthropogenic:* 7 sectors (i.e., power generation, steel industry, shipping, domestic, road and off-road vehicles, railroad, biofuel)	BOND is an emission inventory of primary BC and primary OC aerosols from fossil fuel and biofuel combustion. Data management was handled by the Speciated Pollutant Emission Wizard (SPEW).	**Strengths** • Reflect changes in technology on a national and sectoral basis **Limitations** • Exclude open vegetative burning (e.g. forests) • Significant uncertainties associated with historical reconstruction • Assumption of similar technology transition times between regions is questionable
Junker-Liousse (BC and OC)	Documentation: **https://www.atmos-chem-phys.net/8/1195/2008/acp-8-1195-2008.pdf** Data: **http://eccad.aeris-data.fr**	• Country-by-country estimates • 1° grid size • 1860 – 2003 • *Anthropogenic:* 3 sectors (i.e., traffic, domestic, and industrial)	J&L is a new emission inventory for BC and POC emissions for a period extending back to the beginnings of industrialization based on historical fuel production data.	**Strengths** • Take account of emission factor changes over time using different levels of economic and technological development in each country **Limitations** • High-bias in annual emissions prior to 1988 due to higher BC emission factors of coal in power plants and industrial boilers.
PKU (Peking University; total carbon, BC, OC, PM_{10} and $PM_{2.5}$)	Documentation: **https://pubs-acs-org.ezproxy.neu.edu/doi/pdfplus/10.1021/es5021422** **https://www.ncbi.nlm.nih.gov/pubmed/25347079** Data: **http://inventory.pku.edu.cn/data/data.html**	• Global and country-scale estimates • 0.1° grid size • 1960 – 2014 • *Anthropogenic:* 7 sectors (i.e., oil, coal, gas, biomass combustion, industrial process, waste, non-combustion processes, open fires)	PKU emission inventory is a compilation of global scale high-resolution data products on fuel consumption and emissions of greenhouse gases and air pollutants from all combustion sources.	**Strengths** • Monte Carlo simulation was used throughout the process to address and quantify the uncertainties of the estimations. • Sub-national energy consumption data, empirical models, and proper proxies used **Limitations** • The dependence of energy consumption on certain parameters may not be accurately reflected in the models • Nonorthogonality of some socioeconomic variables are inevitable and the exogeneity of them cannot be totally ensured • Data available for model validation are rather limited • Uncertainty associated with fuel consumption, consequently pollutant emissions, in residential sector
AeroCom phase III (Aerosol Comparisons between Observations and Models)	Documentation: **https://wiki.met.no/aerocom/phase3-experiments** **https://www.atmos-chem-phys.net/17/12911/2017/** Data: **http://aerocom.met.no/data.html**	• Global estimates • 1° grid size • Various years depending on the model experiments	AeroCom, in its phase I, II and III model experiments, has coordinated a series of multi-model studies, using various global emissions (e.g., HTPA, ACCIMP, GFED) to systematically assess the presence and impact of major atmospheric anthropogenic and natural aerosols on climate.	**Strengths** • Assemble a set of model simulations representing the state of the art of aerosol modeling **Limitations** • Large diversity in aerosol simulations between models

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Resource	Website	Geographic resolution, coverage, data period, and sectors included	Brief description	Comments, strengths, limitations
PNNL (Pacific Northwest National Laboratory; SO_2 inventory)	Documentation: **https://www.atmos-chem-phys.net/11/1101/2011/acp-11-1101-2011.pdf**	• Global and country estimates • 0.5° grid size • 1850 – 2005 • *Anthropogenic:* 10 sectors (i.e., coal combustion, petroleum combustion, natural gas processing and combustion, petroleum processing, biomass combustion, shipping bunker fuels, metal smelting, pulp and paper processing, other industrial processes, and agricultural waste burning)	PNNL provide annual estimates of anthropogenic global and regional SO_2 emissions using a bottom-up mass balance method, calibrated to country-level inventory data.	**Strengths** • Sulfur emissions are less uncertain than emissions of most other air pollutants as emissions depend largely on sulfur contents rather than combustion conditions. **Limitation** • Uncertainty in spatial allocation was not assessed
Ito-Penner (BC and OM)	Documentation: **https://pdfs.semanticscholar.org/5881/9a6863f fab1b88da0c2aabf68 5f820b7e01a.pdf**	• Global and country-scale estimates • 1° grid size • 1870 – 2000 • *Anthropogenic:* 2 sectors (i.e., fossil fuel and biomass burning) and subsectors	I&P constructed a data set of historical carbonaceous aerosol emissions, which can be used in trend studies of tropospheric aerosols and in environmental assessments.	**Strength** • Take into account for much of the expected spatial and temporal variations **Limitation** • Only estimated the changes in technology and the resulting net emission factors for emissions from diesel vehicles. Changes in technologies and the division between boiler/furnaces and generators may cause large changes to the historical inventory
Novakov (BC)	Documentation: **https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2002GL016345**	• Global and regional estimates • Not gridded • 1875 – 2000 • *Anthropogenic:* 4 sectors (i.e., residential/commercial, industry, diesel, utilities)	Novakov et al. estimate historical trends of fossil-fuel BC emissions in six regions (e.g., US, UK, China) and extrapolate these to global emissions from 1875 onward.	**Strength** • Spatial and temporal voids in global and, especially, regional BC emissions from fossil fuels were extrapolated **Limitation** • Larger uncertainty in the change in climate forcing for BC
Van Aardenne (CO2, CO, CH4, nonmethane volatile organic compounds, SO_2, NOx, N2O, and NH3)	Documentation: **https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2000GB001265**	• Global and country-scale estimates • 1° grid size • 1890 – 1990 • *Anthropogenic:* 3 sectors (i.e., energy/industry, agriculture/waste, and biomass burning)	An anthropogenic emissions data set constructed for trace gases is based on EDGAR v2.0.	**Strength** • An a priori emission data set for atmospheric models that investigate the effect of long-term trends in the emissions of trace gases **Limitation** • High uncertainties due to limited activity data and emission factors, and use of constant aggregated emission factors for the period of 1890-1970 instead of representative emission factors
CDIAC (Carbon Dioxide Information Analysis Center; CO2)	Documentation: **https://cdiac.ess-dive.lbl.gov/trends/emis/overview_2014.html** Data: **https://data.ess-dive.lbl.gov/view/doi:10.3334/CDIAC/00001_V2017**	• Global, regional and national • 1° grid size • 1751 – 2014 • *Anthropogenic:* 4 sectors (i.e., bunker fuels, gas flaring, calcining limestone, non-fuel uses)	A time series CO2 emission in units of million metric tons of carbon per year from anthropogenic sources for 1950-2014.	**Strength** • Historical (1751) global estimates available **Limitation** • Prone to modeling uncertainties

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Annex 5 | Table 2
Emissions and source apportionment resources
List of regional anthropogenic emission inventories

Resource	Website	Geographic resolution, coverage, data period, and sectors included	Brief description	Comments, strengths, limitations
Global Inventories (all species considered)				
TNO_MACC-III (Monitoring Atmospheric Composition and Climate, Phase III)	Documentation: **https://atmosphere.copernicus.eu/sites/default/files/repository/MACCIII_FinalReport.pdf** **https://www.atmos-chem-phys.net/14/10963/2014/acp-14-10963-2014.pdf**	• Europe • 2000 – 2011 • 0/8x1/16° grid size (~7x7km over central Europe) • *Anthropogenic:* 10 sectors (i.e., power, residential, industry, oil & gas, product use, road transport, other transport, waste, agriculture)	The MACC-III project was the last interim stage in the development of the operational CAMS: its overall objective was to function as the bridge between the developmental precursor projects -GEMS, PROMOTE, MACC and MACC-II- and the start of Copernicus operations.	**Strength** • Year-specific spatial distribution
CAMS_REGv2.0	Documentation: **https://atmosphere.copernicus.eu/sites/default/files/2018-11/5-CAMS_User_workshop_Zagreb_Emissions_TNO.pdf** **https://atmosphere.copernicus.eu/sites/default/files/2018-05/CAMS81_2017SC1_M81.1.1.1-M6-201802_v3_APPROVED_Ver2.pdf**	• Europe • 2000 – 2015 • 0.1°x0.05° grid size (~6x6km over central Europe) • *Anthropogenic* sectors similar to MACC	CAMS_REG inventories are an update of the TNO_MACC, TNO_MACC-II and TNO_MACC-III inventories, using the latest reported data and improvements in the spatial distribution	• Refer to CAMS-GLOBAL
EMEP (European Monitoring and Evaluation Programme)	Documentation: **http://emep.int/publ/reports/2018/EMEP_Status_Report_1_2018.pdf** Data: **http://www.ceip.at/ms/ceip_home1/ceip_home/webdab_emepdatabase/**	• Europe (geographic area between 30°N-82°N latitude and 30°W-90°E longitude) • 1980 – 2016 • 0.5° and 0.1° grid sizes • *Anthropogenic:* 13 sectors (i.e., aviation, non-industrial combustion, public power, industry, shopping, fugitives, other combustion, road and off-road transportation, solvents, agriculture other/livestock, waste)	The inventory for Europe contains national total emissions on main pollutants, heavy metals, persistent organic pollutants and PM, as well as sector data and gridded emission data. Projections for 2020, 2025, 2030 and 2050 are also included in the inventory.	**Strength** • Not reported emissions are gap-filled in order to create complete sectoral gridded emissions for the whole of the EMEP area **Limitation** • The quality of submitted emission data differs significantly across countries, resulting in large uncertainty in the data • Industrial emissions proxies and methodologies should be checked since for all pollutants much lower values than the other inventories are reported.

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Annex 5 | Table 2
Emissions and source apportionment resources
List of regional anthropogenic emission inventories (cont.)

Resource	Website	Geographic resolution, coverage, data period, and sectors included	Brief description	Comments, strengths, limitations
EMP-INERIS (Institut National de l'Environnement Industriel et des Risques)	Documentation: **https://cordis.europa.eu/docs/results/212/212095/final1-final-report-v24nov2011.pdf** **https://www.geosci-model-dev.net/10/2397/2017/gmd-10-2397-2017.pdf**	• Europe • 1998 – 2007 • 0.1° grid size (10x10km2) • *Anthropogenic:* similar to EMEP and MACCity)	The EMEP-INERIS inventory was created by CityZen (megaCITY - Zoom for the ENvironment) Partner INERIS by downscaling the EMEP data to 10x10 km2 resolution, and using landcover data (GLOBCOVER). INERIS uses CHIMERE model for regional atmospheric composition. The EMEP-INERIS inventory has also been implemented in the MACCity inventory (developed by CityZen and partner) through a merge of the INERIS emissions for Europe into the global inventory.	*See above in EMEP.* **Limitation** • The spatial disaggregation of emissions from on-road traffic should be checked for some eastern cities (Bucharest, Sofia) for which much lower values are reported.
JRC07 (Joint Research Centre)	Documentation: **https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/downscaling-methodology-produce-high-resolution-gridded-emission-inventory-support-localcity**	• Europe • 2010 – 2030 • 1/8° and 1/16° grid size (100m) • *Anthropogenic:* 10 sectors (i.e., combustion in energy and transformation industries, non-industrial combustion, manufacturing industry, extraction of fossil fuels, solvent, road transport, other mobile sources, water treatment, agriculture)	The JRC07 inventory is developed for use in Integrated Assessment Modelling strategies (IAM) in the fields of regional air-quality and land use and territorial modelling (LUiSA). The inventory is based on country total emission data from GAINS.	**Strength** • High spatial and sectoral resolution emission inventory with multi-temporal scenarios up to year 2030. **Limitation** • The country inter-variability of urban residential emissions (Wood and Coal burning) in Eastern Europe has not been properly addressed
NAEI (National Atmospheric Emissions Inventory)	Documentation: **https://naei.beis.gov.uk/** Data: **http://naei.beis.gov.uk/data/**	• United Kingdom • 1990 – 2016 • 1km gird resolution • *Anthropogenic:* 11 sectors (e.g., combustion in various sectors, production, extraction/distribution of fossil fuels, solvent, road transport, other transport, waste treatment, agricultural/forests, others)	The NAEI estimates annual pollutant emissions from 1970 to the most current publication year for the majority of air quality pollutants and GHGs.	**Strength** • Inventory is based on highly detailed calculation methods, assumptions and representative measurements on the amount of each air pollutant generated from different activities and the level of that activity in the UK. **Limitation** • Uncertainties associated with the availability and quality of the activity data, emission factors and methodologies used in emissions calculations throughout the time series
EPA-NEI (Environmental Protection Agency; National Emissions Inventory)	Documentation: **https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data**	• United States • 1970 – 2017 • Not gridded • *Anthropogenic:* 4 sectors and their subsectors (i.e., stationary fuel combustion, industrial and other combustion, transportation, miscellaneous)	These data were obtained through the EPA's National Emissions Inventory Air Pollutant Emissions Trends Data database. The trends shown are for criteria air pollutants and precursors covered by the National Ambient Air Quality Standards, excluding lead.	**Strength** • Improved inventory estimation methods and newly available data are applied 'backwards' to previous year trend estimates. **Limitation** • The EPA trends data sets do not include information for BC. • The modeling files did not include data for locomotive, commercial marine vessels and aircrafts

Annex 5 | Table 2

Emissions and source apportionment resources

List of regional anthropogenic emission inventories (cont.)

Resource	Website	Geographic resolution, coverage, data period, and sectors included	Brief description	Comments, strengths, limitations
REAS v2.1 (Regional Emission inventory in Asia)	Documentation **https://www.atmos-chem-phys.net/13/11019/2013/acp-13-11019-2013.html** Data: **https://www.nies.go.jp/REAS/**	• East, Southeast, South, and Central Asia. Asian part of Russia • 2000 – 2008 • 0.25° grid size • *Anthropogenic:* 4 sectors and their subsectors [i.e., fuel combustions; industrial process; agricultural activities; and others (fugitive emissions, solvent use, human, etc.)	REAS integrates historical, present, and future emissions in Asia using a consistent methodology; it uses representative emission factors for each sector. Earlier version of REAS focus on 1980 – 2003 for historical emissions and 2010 – 2020 for future projections.	Strength • Updated emission factors in China, and activity data. • Improved computational power and atmospheric chemistry models at higher spatial and temporal resolutions. Limitation • Larger uncertainties in emission inventory in Southeast and South Asian countries
TRACE-P & INTEX-B from the ACCESS system (ACE Asia and Trace-P Modeling and Emission Support System)	Documentation: **https://www-air.larc.nasa.gov/missions/intex-b/intexb.html** Data: **https://www-air.larc.nasa.gov/missions/intex-b/dataaccess.htm**	• Asian countries (e.g., Mexico City Megaplex) • 2006 • 0.5° grid size • *Anthropogenic:* 8 sectors (i.e., residential combustion or non-combustion, industrial combustion or non-combustion, on-road or off-road transportation, power, other) and source regions (e.g., Siberian, Japanese, Chinese)	The TRACE-P (2001) and INTEX-B (2006) quantify the transpacific transport and evolution of Asian pollution to North America and assess its implications for regional air quality and climate. Both inventories are distributed as part of ACCESS.	Strength • Validate and refine satellite observations of tropospheric composition. • Map emissions of trace gases and aerosols and relate atmospheric composition to sources and sinks. Limitation • Short-term trends of the Asian atmospheric environment
MEIC (Multi-resolution Emission Inventory for China)	Documentation: **http://www.meicmodel.org** **https://academic.oup.com/nsr/article/4/6/834/4775139**	• Mainland China • 0.2°, 0.5°, and 1° grid size • 1990 – 2015 • *Anthropogenic:* 6 sectors (i.e., power, industry, residential, transportation, solvent use, agriculture)	MEIC is a technology-based bottom up anthropogenic emissions of ten air pollutants and greenhouse gases over China.	Strength • The MEIC model is based on a series of improved emission inventory models with high-resolution mapping of emissions for power plants and on-road vehicles Limitation • Tend to overestimate emissions in urban centers but underestimate emissions in rural areas, leading to unrealistically higher urban–rural emission gradients
Garg	Documentation: **https://www.sciencedirect.com/science/article/pii/S1352231006003645**	• India • 1985 – 2005 • Not gridded • *Anthropogenic:* 12 sectors (i.e., power, road, rail, navigation, aviation, cement, steel, brick, other industries, biomass burning, nitric acid production, others)	The Garg inventory uses the data provided by international activity databases such as the IEA, as well as data from national, state and district level administrations in India to provide emission trends of GHG and local air pollutants.	Strength • Use actual activity data (to the extent available) for various source categories for all gases for the study period • Use India-specific emission factors to a large extent Limitation • Not updated to recent year

Annex 5 | Table 2
Emissions and source apportionment resources
List of regional anthropogenic emission inventories (cont.)

Resource	Website	Geographic resolution, coverage, data period, and sectors included	Brief description	Comments, strengths, limitations
Urban Emissions **APnA** (Air Pollution knowledge Assessments) **IAQI** (India Air Quality Information)	Documentation: **https://www.sciencedirect.com/science/article/pii/S2212095518302402** **https://www.sciencedirect.com/science/article/pii/S1309104218304835** **http://www.indiaairquality.info**	• India - National and Urban scale • 2010 – 2030 • 0.01° grid size (~1km) for 50 Indian cities • 0.25° grid size (~25km) for all India • Multiple sectors (i.e., transport (road, rail, aviation, and shipping), domestic (cooking, space heating, and lighting), dust (road resuspension, wind erosion, and construction activities), industries (heavy industry like brick kilns, iron and steel, refineries, fertilizers, mineral processing, cement, power plants, quarries, and light industries), open waste burning (in situ and landfills), diesel generator sets, outside/regional sources (open fires, lightning, sea salt, dust storms, and not-India inventory for the Sub-continent)	An updated bottom-up multi-pollutant emissions inventory for the base year 2010 and $PM_{2.5}$ source apportionment based on chemical transport modeling for local and non-local sources.	**Strength** • Dynamically updated inventory linked to regional and urban meteorological parameters (for sectors like transport, space heating, construction, and dust) and big data like gridded speed maps from google maps • The emissions inventory is currently in use for 3-day advance air quality forecasting for public release on an on-going basis, including real-time comparison of the forecasts with on-ground monitoring data. **Limitation** • Prone to modeling uncertainties
DICE-Africa (Diffuse and Inefficient Combustion Emissions in Africa)	Documentation: **https://pubs.acs.org › doi › abs › acs.est.6b02602** Data: **https://www2.acom.ucar.edu/modeling/dice-africa**	• Africa • 2006 and 2013 • 0.1° grid size • *Anthropogenic:* 8 sectors (i.e., solid biofuels, charcoal production, kerosene, backup generators, cars, motorcycles, gas flaring, and ad hoc oil refining)	DICE-Africa is an updated inventory of pollution from diffuse and inefficient combustion sources in Africa, which may be associated with rapid population growth.	**Strength** • The inventory is incorporated in the GEOS-Chem CTM to assess the impact of DICE-Africa on ambient air quality. **Limitation** • Due to data limitations, the inventory has few chemical compound emissions for kerosene, and many sources are missing where there is no data available (e.g. road dust, electronic waste fires).
Assamoi-Liousse	Documentation: **http://iopscience.iop.org/article/10.1088/1748-9326/9/3/035003**	• Africa • 2005 and 2030 • 0.25° grid size • *Anthropogenic:* combustion of fossil fuels and biofuels (e.g., use of diesel fuels, animal waste, fuelwood, charcoal making and coal)	An inventory of African combustion emissions, which provides emissions for 2005. Three scenarios are considered for the 2005–2030 period. The inventory considers emissions that are specific to Africa. Emissions were calculated based on method used in Junker and Liousse (see above).	**Strength** • An integrative inventory taking into account both particles and gases using the same methodology **Limitation** • Similar to many inventories, large uncertainties in the emission estimates due to lack of adequate data.

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Annex 5 | Table 3
Emissions and source apportionment resources
List of inventories for biomass burning emission

Resource	Website	Geographic resolution, coverage, data period, and sectors included	Brief description	Comments, strengths, limitations
Global inventory of biomass burning				
GFAS (Global Fire Assimilation System)	Documentation: **https://www.biogeosciences.net/9/527/2012/** Data: **http:// apps.ecmwf.int/datasets/data/cams-gfas/**	• Global and regional • 0.1° grid size • 2003 – present	GFAS data is a time-series of daily biomass burning emissions (top-down approach) by assimilating FRP observations from the MODIS instruments onboard the Terra and Aqua satellites. The emission estimates are provided to the atmospheric composition model operated by CAMS: the Integrated Forecasting System.	**Strength** • Detects fires in real time at high spatial and temporal resolution, as well as small fires **Limitation** • Limited sampling frequency of the MODIS FRP product.
GFED4 **(**Global Fire Emissions Database)	Documentation: **https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/jgrg.20042** **https://www.earth-syst-sci-data.net/9/697/2017/essd-9-697-2017.pdf** Data: **https://www.globalfiredata.org/data.html** **https://daac.ornl.gov/VEGETATION/guides/fire_emissions_v4_R1.html**	• Global and regional • 0.25° grid size • 1997 – present (and Jul 1995 – Jun 1996) • *Sector:* 6 fire types (including agricultural waste burning, boreal forest fires, deforestation fires, peatland fires, and savanna fires)	GFED4 provides global time-series estimates of burned area and fire emission (bottom-up approach), and fractional contributions of different fire types. The inventory is developing using satellite (MODIS Burned Area) information on fire activity and vegetation productivity. GFED4s refers to GFED4 with small fires.	**Strength** • The new emission estimates are made using a higher-resolution set of emission factors. Burned area algorithms have been improved considerably since earlier versions, and now include a preliminary estimate of the impact of small fires. **Limitation** • Not including small fires results in a underestimation of emissions • Uncertainties of the new emission estimates remain substantial and are difficult to quantify.
FINN (Fire Inventory from NCAR)	Documentation: **https://www2.acom.ucar.edu/modeling/finn-fire-inventory-ncar** **https://pubs.acs.org/doi/abs/10.1021/es502250z** Data: **http://bai.acom.ucar.edu/Data/fire/**	• Global, regional • 2002 – present • 1km grid size • *Sector:* open biomass burning (including wildfire, agricultural fires, and prescribed burning)	FINN uses satellite observations of active fires (MODIS thermal anomalies) and land cover, together with emission factors and estimated fuel loadings to provide daily, high-resolution, global estimates of GHGs, reactive trace gases, PM, and toxic emission from the open waste combustion (bottom-up approach).	**Strength** • Near-real-time based on Rapid Response MODIS fire counts • It is ready to use with WRF/Chem **Limitation** • Underestimation of the number of fires due to missing fires • Satellite overpass timing and cloud cover may prevent the detection of fires • Overestimating the size of the small fires that are detected • Uncertain relationship between fire detections and area burned • Identification of the land cover
QFEDv3.1 (Quick Fire Emissions Dataset)	Documentation: **https://gmao.gsfc.nasa.gov/research/science_snapshots/global_fire_emissions.php** Data: **http://ftp.as.harvard.edu/gcgrid/data/ExtData/HEMCO/QFED/v2018-07/**	• Global, regional • 2000 – present • 0.1°, 0.25°x0.3125° grid size (1km horizontal)	QFED uses satellite observations (MODIS Active Fire Product) of FRP to estimate near-real-time biomass-burning emissions of atmospheric constituents, and is included in the NASA Goddard Earth Observing System (GEOS) modeling and data assimilation systems (top-down approach).	**Strength** • Good coverage over higher latitudes • Employs more sophisticated treatment of non-observed (e.g., obscured by clouds) land areas. **Limitation** • Has smaller area of detected fires • Caution when using this emission in other models besides GEOS-5.

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Annex 5 | Table 3
Emissions and source apportionment resources
List of inventories for biomass burning emission (cont.)

Resource	Website	Geographic resolution, coverage, data period, and sectors included	Brief description	Comments, strengths, limitations
GBBEPx v2 (Blended Global Biomass Burning Emissions Product from MODIS and Geostationary Satellites)	Documentation: **https://www.ospo.noaa.gov/Products/land/gbbepx/docs/GBBEPx_EUM.pdf** Data: **https://satepsanone.nesdis.noaa.gov/pub/FIRE/GBBEPx/**	• Global, regional • 2000 – present • 0.25^ox0.3125^o grid size	GBBEPx produces daily global biomass burning emissions blended fire observations from MODIS, VIIRS, and geostationary satellites (a blended QFED and GBBEP-Geo).	**Strength** • Typically has greater emission values overall • Developed using diurnal patterns of FRP which reduces impacts of missing fire observations caused by cloud cover, sensor saturation. **Limitation** • Detect less fires over higher latitudes
FEER (Fire Energetics and Emissions Research)	Documentation: **https://www.atmos-chem-phys.net/14/6643/2014/** Data: **https://feer.gsfc.nasa.gov/data/emissions/**	• Global, regional • 2003 – present • 0.1^o grid size	FEER develops a global gridded fire energy (i.e., emission coefficients) product for smoke total particulate matter (TPM) based on a top-down approach using coincident measurements of FRP and AOT from the MODIS, as well as global emission product, converted from time-integrated FRP data from the GFAS product to calculate regional smoke TPM emissions.	**Strength** • Top-down approach (in relation to the emission coefficients used) means closer resemblance to satellite observations of aerosols **Limitation** • Did not have emission coefficients for smoke constituent species (e.g., OC, BC, $PM_{2.5}$)
FLAMBE (Fire Locating and Modeling of Burning Emissions)	Documentation: **https://ieeexplore.ieee.org/document/5208306** Data: **www.nrlmry.navy.mil/flambe/**	• Global, regional • 2000 – 2017 • 1^o grid size	FLAMBE provides hourly burned areas and carbon emissions based on both MODIS and Geostationary Operational Environmental Satellites (GOES) fire counts (bottom-up approach).	**Limitation** • Do not specifically contain BC and OC emission
IS4FIRESv2.0 **(Integrated System for Wild-Land Fires)**	Documentation & data: **https://is4fires.fmi.fi/**	• Global, regional • March 2000 – 2017 • 0.1^o grid size • *Sector:* wild-land fires from boreal, temperate and tropical forests, residual crop, grass, shrub and peat.	IS4FIRES inventory provides daily, high-spatially resolved emission fluxes originated from wild-land fires. It captures major wildland fires using satellite remote sensing (MODIS), modelling both the fire spread and the atmospheric dispersion of the fire plume, and to determine the source areas using a combination of ground-based air quality, measurements and a long-range transport modelling system.	**Strength** • The system relies on direct scaling from fire intensity to emission fluxes, avoiding uncertainties of burnt-area based approaches and allowing explicit considerations of individual or closely-located fires.

Regional inventory of biomass burning

Resource	Website	Geographic resolution, coverage, data period, and sectors included	Brief description	Comments, strengths, limitations
AMMABB **(African Monsoon Multidisciplinary Analyses - Biomass Burning emission inventory)**	Documentation: **https://www.atmos-chem-phys.net/10/9631/2010/acp-10-9631-2010.pdf**	• Africa • 2000 and 2007 • 0.5^o grid size (up to 1km) • Emissions from savannas, forests and agricultural fires	A daily African biomass burning inventory for gaseous and particulate species.	**Strength** • The inventory was well reproduced by the global model when using updated biomass burning emissions **Limitation** • Large uncertainties inherent in the determination of biomass burning emissions
WFEI **(Wildland Fire Emission Inventory)**	Documentation: **https://www.atmos-chem-phys.net/11/12973/2011/**	• Contiguous US • 2003 – 2008 • 500 m, daily resolution • CO and $PM_{2.5}$ emissions	WFEI is a high-resolution model for non-agricultural open biomass burning in the contiguous United States.	**Strength** • The model combines observations from the MODIS sensors on the Terra and Aqua satellites, meteorological analyses, fuel loading maps, an emission factor database, and fuel consumption models to estimate emissions from wildland fire.

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Annex 5 | Table 4
Emissions and source apportionment resources
Examples of emission factor databases

Resource	Website	Brief description	Characteristics
Compilation of air pollutant emissions factors (AP-42)	Documentation: **https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors**	AP-42 is the primary compilation of US EPA's emissions factor information. It contains emissions factors and process information for more than 200 air pollution source categories.	The extent of completeness and detail of the emission information in AP-42 is determined only by the information available from published references. Emission factors in AP-42 are neither EPA-recommended emission limits (e. g., best available control technology) nor standards (e. g., National Emission Standard for Hazardous Air Pollutants or NESHAP).
European Monitoring and Evaluation Programme (EMEP)/European Environmental Agency (EEA) air pollutant emission inventory	Technical guidebook: **https://www.eea.europa.eu/publications/emep-eea-guidebook-2019** Emission factor database: **http://efdb.apps.eea.europa.eu/**	The Guidebook has two key functions: to provide procedures to enable users to compile emission inventories that meet quality criteria for transparency, consistency, completeness, comparability and accuracy, and to provide estimation methods and emission factors for inventory compilers at various levels of sophistication.	• Caution when using the methodologies in the Guideline to compile inventories for developing countries - where technologies and practices may differ radically from those used in industrialized countries. • Limited provision of emission factors for organic carbon.
National Atmospheric Emissions Inventory	**https://naei.beis.gov.uk/data/ef-all**	The database contains emission factors detailed by source and fuel.	• Emission factors are specifically for the United Kingdom only.
The Co-ordinated European Programme on Particulate Matter Emission Inventories, Projections and Guidance (CEPMEIP) Emission Factor Database	**http://www.air.sk/tno/cepmeip/**	CEPMEIP develops default methods and emission factors for the use of national experts when reporting particulate matter emission inventories to the European Monitoring and Evaluation Programme.	• Emission factors are derived from international literature, and may be different from locally derived estimates.

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Annex 6
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**

Annex 7
International Organizations & Agencies to Support Urban Air Quality Work

Type	Organization/Agency	URL
International NGOs	Climate and Clean Air Coalition	https://ccacoalition.org/en
	Clean Air Asia	https://cleanairasia.org/
	Clean Air Institute	https://www.cleanairinstitute.org/
	C40	https://www.c40.org/
	Vital Strategies	https://www.vitalstrategies.org/
Global, multinational organizations	WHO	https://www.who.int/
	UNDP (United Nations Development Programme)	https://www.undp.org/
	UNEP (United Nations Environment Programme)	https://www.unenvironment.org/
	UNICEF	https://www.unicef.org/
	World Bank	https://www.worldbank.org/
Regional multinational organizations	The African Union (AU)	https://www.ecowas.int/
	ASEAN (Association of Southeast Asian Nations)	https://asean.org/
	ECOWAS (Economic Community of West African States)	https://www.ecowas.int/
Research partnerships	Global Environmental and Occupational Health (GEOHealth)	https://www.fic.nih.gov/Programs/Pages/environmental-occupational.aspx
US Government Agencies	EPA (Environmental Protection Agency)	https://www.epa.gov/
	South Coast Air Quality Management District	http://www.aqmd.gov/
	NASA (National Aeronautics and Space Administration)	https://www.nasa.gov/
	Department of State: embassies, regional Environmental Offices and air quality fel-lows	https://www.state.gov/

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