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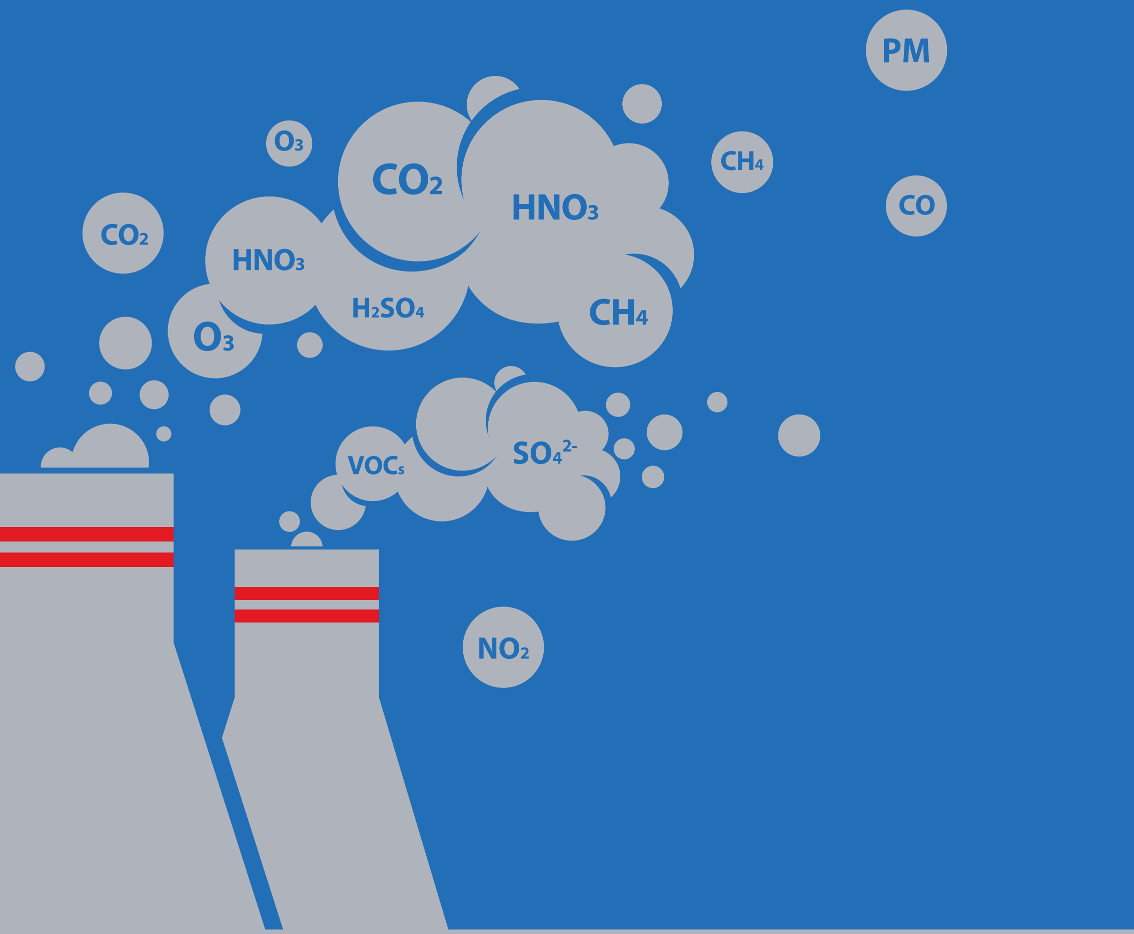
Air Pollution:
An Introduction to Its Causes, Effects, and Solutions

2021. 1



Ministry of Foreign Affairs of the Republic of Korea
National Council on Climate and Air Quality of the Republic of Korea

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An Introduction to Its Causes, Effects, and Solutions

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This publication was written by Laura Hyesung Yang, Jiwon Kim, and Dha Hyun Ahn (Yonsei University), with substantive inputs from Sangmin Nam, Minkyung Hong (UNESCAP), and Jhoon Kim (Yonsei University). The authors appreciate Yeora Chae (KEI), Ho-Jin Lim (KNU), and Chang-Keun Song (UNIST) for their review of the draft and valuable comments.

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Contents

Figures

Tables

Box

Acronyms and Abbreviations

AATHP	ASEAN Agreement on Transboundary Haze Pollution
AE	Angstrom exponent
AOD	aerosol optical depth
AQG	Air Quality Guidelines
AQHI	Air Quality Health Index
AQI	Air Quality Index
AQMS	Air Quality Management System
ASEAN	Association of Southeast Asian Nations
BC	black carbon
CAI	Comprehensive Air-quality Index
CCAC	Clean Air and Climate Coalition
CH_4	methane
COPD	chronic obstructive pulmonary disease
CO	carbon monoxide
CO_2	carbon dioxide
EEA	European Environmental Agency
EMEP	European Monitoring and Evaluation Programme
FAO	Food and Agriculture Organization of the United Nations GDP Gross Domestic Product
GEMS	Geostationary Environment Monitoring Spectrometer GEO Geostationary Earth Orbit
GHGs	greenhouse gases
H_2O	water
HFCs	hydrofluorocarbons
HNO_3	nitric acid
IHME	Institute for Health Metrics and Evaluation
IPCC	Intergovernmental Panel on Climate Change
LEO	Low Earth Orbit
LRTAP	Long-range Transboundary Air Pollution
MODIS	Moderate resolution Imaging Spectroradiometer
N_2	atmospheric nitrogen
N_2O	nitrous oxide
NASA	National Aeronautics and Space Administration
NEACAP	North-East Asia Clean Air Partnership
NEASPEC	North-East Asian Subregional Programme for Environmental Cooperation

NF_3	Nitrogen trifluoride
NH_3	ammonia
NH_3^0	unionized ammonia
NH_4^+	ionized ammonia
NMVOC	nonmethane volatile organic compounds
NO	nitric oxide
NO_2	Nitrogen dioxide
NOAA	National Oceanic and Atmospheric Administration
NO_X	nitrogen oxides
O_3	ozone
OC	organic carbon
OECD	Organisation for Economic Co-operation and Development
OH	hydroxyl radical
PFCs	perfluorocarbons
PM	particulate matter
POPs	Persistent Organic Pollutants
PSI	Pollutant Standards Index
SDGs	Sustainable Development Goals
SF_6	hexafluoride
SO_2	sulfur dioxide
SO_4^{2-}	sulfate
SO_3^{2-}	sulfite
SO_X	sulfur oxides
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNESCAP	United Nations Economic and Social Commission for Asia and the Pacific
UNFCCC	United Nations Framework Convention on Climate Change
UNGA	United Nations General Assembly
US EPA	United States Environmental Protection Agency
USD	US Dollar
UV	ultraviolet
VOC	volatile organic compounds
WHO	World Health Organization
WMO	World Meteorological Organization
WTP	Willingness-to-pay

Introduction

Introduction

Air pollution is the world's largest environmental threat to human health and one of the major preventable causes of death and disease. According to WHO, the ambient and household air pollution together account for 7 million premature deaths globally every year, making it more deadly than a combination of malaria, tuberculosis, and AIDS. In particular, an estimated 4.2 million people die prematurely around the world due to ambient air pollution, mostly from heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and acute respiratory infections in children. It disproportionately affects women, children, and the elderly in developing nations, who are frequently exposed to ambient and indoor air pollution.

Source: UN Photo/Kibae Park

The United Nations General Assembly (UNGA) in December 2019 adopted the Resolution 74/212 that designates September 7 as the International Day of Clean Air for blue skies to raise awareness at all levels – individual, community, corporate, and government – that clean air is vital for health, productivity, the economy, and the environment. The Resolution underlines the importance and necessity to promote and facilitate actions to improve air quality. To this end, it stresses the need to strengthen international cooperation at the global, regional, and subregional levels in various areas related to improving air quality, including the collection and utilization of data, joint research and development, as well as the sharing of best practices.

The International Day of Clean Air for blue skies was advocated by the Republic of Korea. The Resolution to hold the International Day of Clean Air for blue skies is a follow-up of the previous resolutions that were adopted by the United Nations Environment Assembly in its Resolution 3/8 of December 6, 2017, World Health Assembly in its Resolution 68.8 of May 26, 2015, and the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) in its Resolution 75/4 of May 31, 2019 that emphasize the significance of addressing the health impact of air pollution and strengthening international cooperation to tackle air pollution challenges.

Against this backdrop, this Handbook was prepared as a reference for the International Day of Clean Air for blue skies. The official theme for the first International Day in 2020 is "Clean Air for All" with the goal of enhancing global solidarity and political momentum for actions against air pollution and climate change. The Handbook provides a guide to different stakeholders to join the collaborative efforts to address air pollution and contribute to the observance of this International Day.

Chapter 1

Current Air Pollution Situation and Trend

1 Trend of Global Death Rate Attributable to Air Pollution

2 Annual Death Rate Attributable to Air Pollution by Regions/Countries

3 Global Air Pollution Exposure Level

Chapter 1

Current Air Pollution Situation and Trend

1 Trend of Global Death Rate Attributable to Air Pollution

Air pollution is generally caused by gas-phase pollutants (e.g., ozone, nitrogen dioxide, sulfur dioxide, carbon monoxide and etc.) and particulate matter especially particles less than 2.5 μm in diameter ($PM_{2.5}$). In recent decades, the global death attributable to air pollution has shown a decreasing trend, mainly because of the reduced indoor air pollution, while outdoor particulate matter and ozone pollution are exhibiting minor changes.

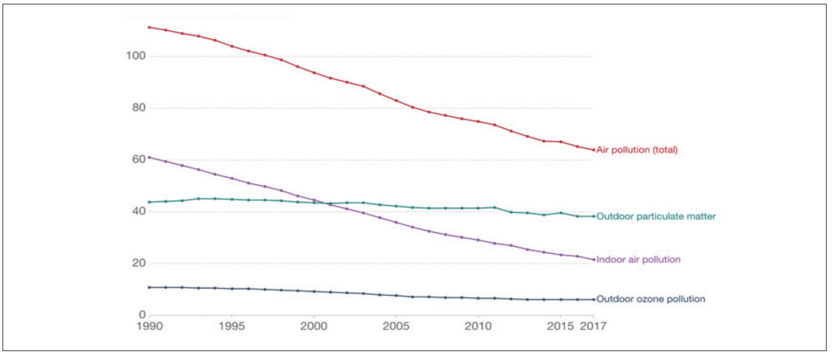


Figure 1.1. Age-Standardized Global Death Rate from Air Pollution per 100,000 Population since 1990. [Data Source: IHME, Global Burden of Disease (2017), Graph Source: Ritchie, H. (2017)]

2 Annual Death Rate Attributable to Air Pollution by Regions/Countries

By region, Africa exhibits the highest deaths per 100,000 people from the ambient and household air pollution, combined with 180.9 deaths annually, followed by South-East Asia with 165.8 deaths. Europe and the Americas experience much fewer deaths from air pollution with 29.7 and 36.3 deaths per 100,000 people respectively.

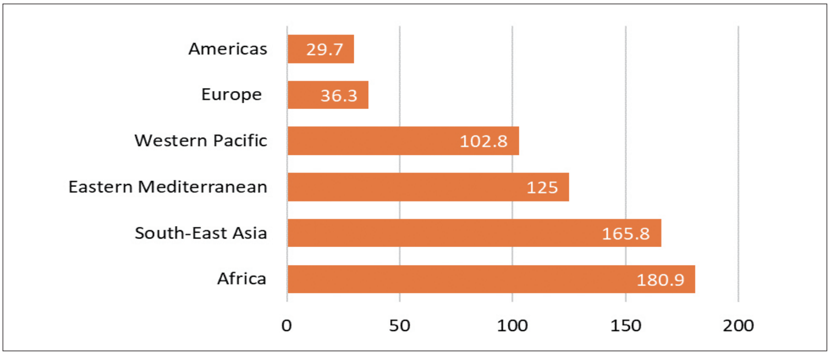


Figure 1.2A. Age-Standardized Death Attributable to Ambient and Indoor Air Pollution (death rate per 100,000 population) as of 2016. (Data Source: WHO, 2018)

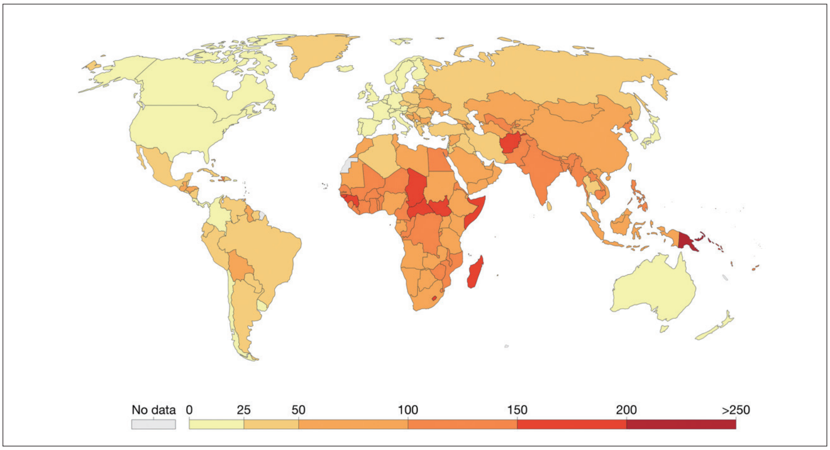


Figure 1.2B. Age-Standardized Death Attributable to Ambient and Indoor Air Pollution (death rate per 100,000 population) shown on global map as of 2017. [Data Source: IHME, Global Burden of Disease, Graph Source: Ritchie, H. (2017)]

The figure below exhibits the change in death rate in 1990 as compared to the death rate in 2017 attributable to air pollution. If the country is placed on the line, this indicates no change in the death rate between two time periods. If the country is placed above the line, the country experienced a decrease in mortality rate in 2017 as compared to the past. More specifically, at the country level, middle-to-high income countries like Australia, China, Germany, and the United States experienced a smaller number of deaths in 2017 than in 1990. On the other hand, there were more deaths in developing countries like India, Nepal, and South America during the same period.

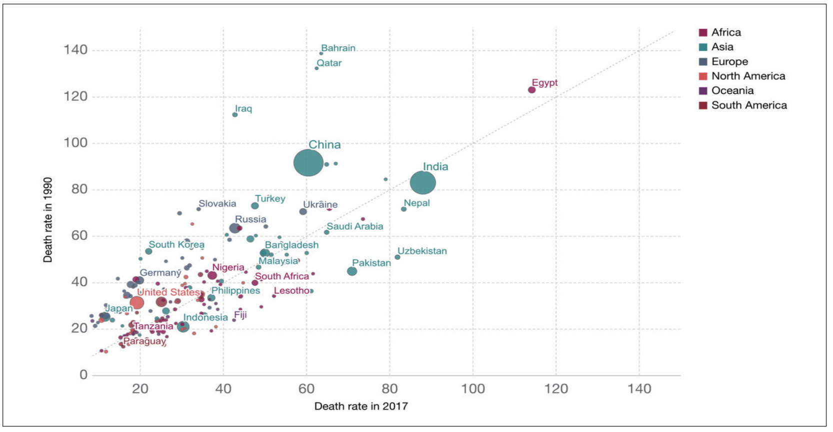


Figure 1.2C. Age-standardized Number of Death (per 100,000 individual) in 1990 versus 2017. [Data Source: IHME, Global Burden of Disease, Graph Source: Ritchie, H. (2017)]

3 Global Air Pollution Exposure Level

The exposure to air pollution is particularly high for people living in Asia and Africa as compared to people residing in America and Europe. For instance, the exposure level of $PM_{2.5}$ annual average in East Asia and Pacific regions is 43 $\mu g/m^3$ and Sub-Saharan Africa is 67 $\mu g/m^3$ respectively. On the other hand, the annual average $PM_{2.5}$ exposure in North America is 9 $\mu g/m^3$ and that of the European Union is 14 $\mu g/m^3$. Therefore, the exposure level can be 7 orders of magnitude higher for the population in Africa as compared to people in North America. Moreover, 95% of the world population is currently exposed to $PM_{2.5}$ higher than 10 $\mu g/m^3$, which is the recommended standard by the WHO to reduce deaths attributable to air pollution by 15%. 95% of the world population not only includes people in Asia and Africa but also people in Europe and South America.

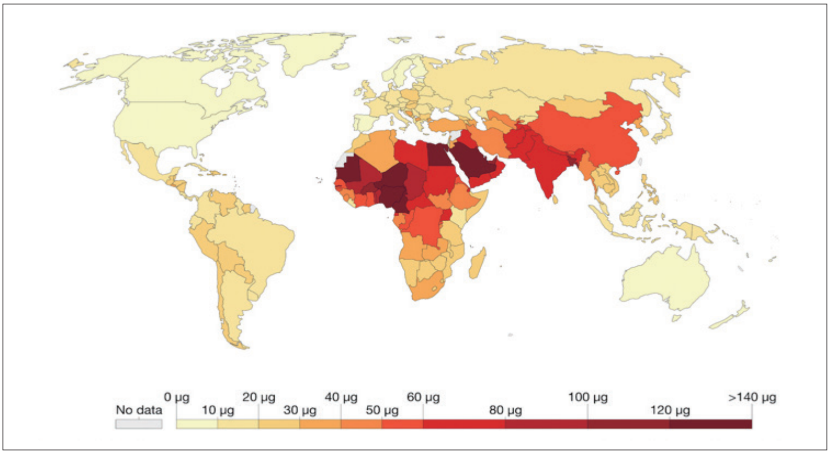


Figure 1.3. Population-weighted Mean Exposure to $PM_{2.5}$ Concentration in a Spatial Map, 2016. [Data Source: World Bank (2016), Graph Source: Ritchie, H. (2017)]

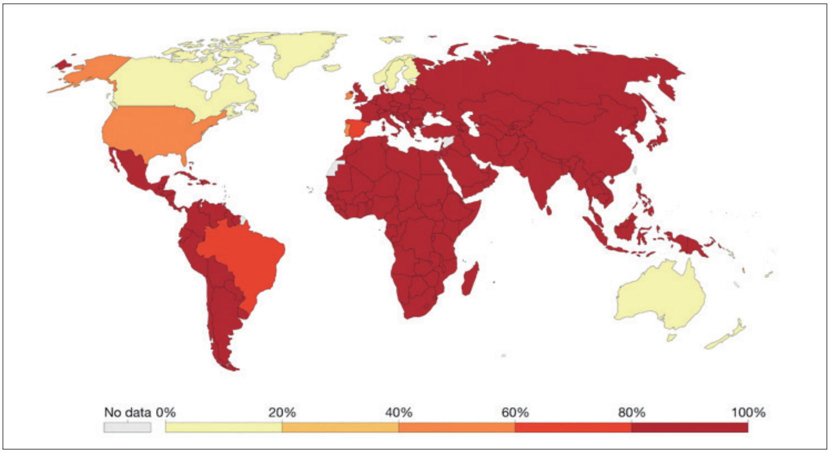


Figure 1.4. Proportion of Population Exposed to PM2.5 Concentration Level Exceeding WHO's Guideline as of 2016. [Source of Data: World Bank (2016), Graph Source: Ritchie, H. (2019)]

Chapter 2

What are the Most Common Air Pollutants?

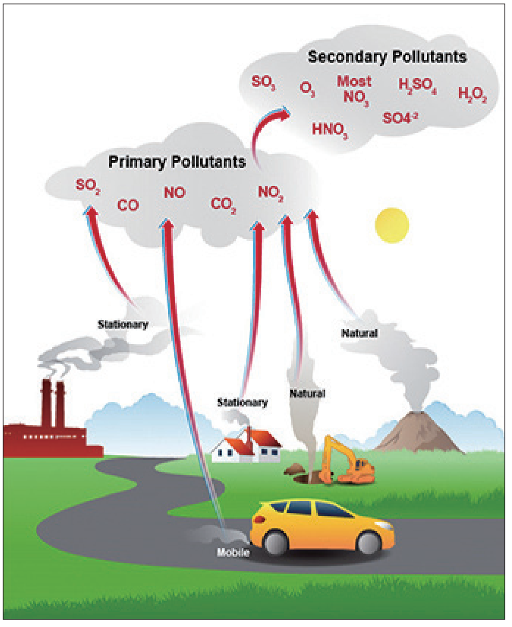
1 Types of Pollutants: Primary and Secondary Air Pollutants

2 Main Pollutants and Their Properties

Chapter 2

What are the Most Common Air Pollutants?

1 Types of Pollutants: Primary and Secondary Air Pollutants



Source: US EPA

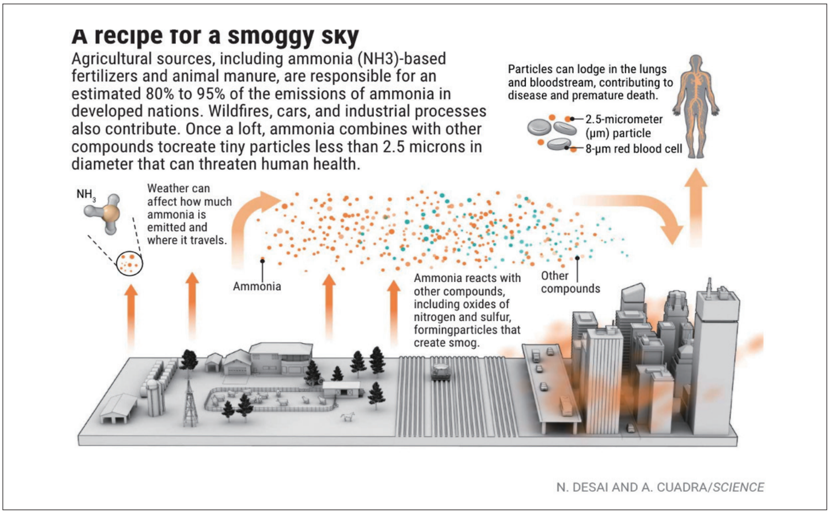
Air pollutants can be broadly divided into two categories based on the source: primary air pollutants and secondary air pollutants. Primary air pollutants are air pollutants that are directly emitted from sources like factories, cars, etc. Examples include carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), volatile organic compounds (VOC_s), ammonia (NH_3), and sulfur dioxide (SO_2), and nitric oxide (NO). Secondary air pollutants are air pollutants that are generated in the atmosphere through a series of chemical reactions. Examples include particulate matter (PM), ozone (O_3), nitric acid (HNO_3), sulfate (SO_4^{2-}), sulfuric acid (H_2SO_4). Pollutants such as PM and nitrogen dioxide (NO_2) are both primary and secondary pollutants.

2 Main Pollutants and Their Properties

Ammonia (NH_3)

Definition and Properties of Ammonia. NH_3 is a colorless toxic gas with a strong odor that can irritate the eyes and respiratory system when exposed at high levels. Once released, ammonia gas reacts with other air pollutants like nitrogen oxides or sulfur dioxide, and further contributes to the formation of secondary small particles (e.g., ammonium sulfate, and ammonium nitrate) with a diameter that is smaller than 2.5 ($PM_{2.5}$). It is an often-overlooked important ingredient of smog, which is a deadly combination of smoke and fog. This makes NH_3 a primary pollutant that can lead to a generation of secondary air pollutants. It is harder to track NH_3 with monitoring instruments than other pollutants because it readily combines with other chemical compounds that are present in the ambient air. Due to the difficulty in monitoring and tracking ammonia, the regulations are not properly established in many parts of the world.

Sources of Ammonia. Livestock agriculture, such as animal urine, manures, and the utilization of nitrogen fertilizer, is the major source of NH_3 that accounts for 80 to 95% of ammonia emission in developed countries. NH_3 emissions are projected to rise as the demand for chemical fertilizer is continuously increasing. Other sources of NH_3 include vehicles via catalytic converters, sewage works, industrial and combustion processes, and wildfires.



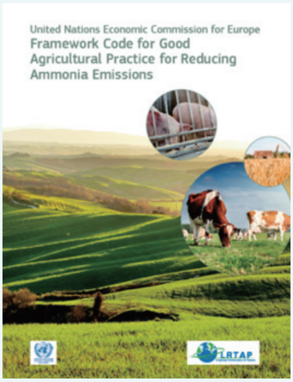
Source: Desai and Caudra/Science

Impacts of Ammonia on the Ecosystem. In the aquatic environment, NH_3 exists either in an ionized (NH_4^+) or unionized form (NH_3^0). The unionized form is toxic in the water environment, while the ionized form is toxic when present inside the fish's body. NH_3^0 can easily enter the fish's body, transform into the ionized form, cause stress on the fish's cells, and prevent its growth. If NH_3^0 is present at a higher level in an aquatic environment, it can even kill fish with increased toxicity. Ammonium-based fertilizers (e.g. ammonium nitrate fertilizer) also induce soil acidification since ammonium undergoes transformation to nitrate (a chemical process called nitrification) in soil and such process releases hydrogen ion (H^+) that reduces the pH of the soil and acidifies the soil. Moreover, a run-off of NH_3 from agriculture can cause eutrophication, a rich nutrient in water that creates algae or aquatic plant bloom that consumes dissolved oxygen in the water that ultimately suffocates aquatic lives. In Europe, NH_3 is expected to be the greatest source of secondary PM, acidification, and eutrophication.

Impacts of Ammonia on Health. NH_3 can also have an adverse impact on health for being corrosive. Exposure to a high concentration of NH_3

can lead to ammonia poisoning. Also, secondary PM generated from NH_3 can cause asthma, bronchitis, and heart complications.

Box 2.1. **Europe's Exemplary Initiative for Controlling Ammonia Emission**



The United Nations Economic Commission for Europe (ECE) Ammonia Abatement Expert Group. The ECE formed an expert group on Ammonia Abatement to guide for reducing ammonia through good agricultural practice. Such initiative started to help meet the Gothenburg Protocol, which aimed to decrease four major pollutants (i.e. sulfur and nitrogen oxides, volatile organic compounds, and ammonia) in 2010 to the 2020-time frame. The "Framework Code for Good Agricultural Practice for Reducing Ammonia Emission" is the official document provided by UNECE, which contains the scientific-based recommendations to reduce the ammonia level. The European Environment Agency (EEA) member countries (EEA-33) achieved the reduction of agricultural emission by 25% in 2011, as compared to 1990.

Read the Framework Code for Good Agricultural Practice for Reducing Ammonia Emission:
https://www.unece.org/index.php?id=41358

Carbon Monoxide (CO)

Definition and Properties of Carbon Monoxide. CO is a poisonous, colorless, and odorless flammable gas. CO is slow to react with the ambient air with other chemical compounds, and it stays in the atmosphere for a long time, from 0.1 to 5 years. CO is a man-made primary pollutant and also an ingredient for forming ground-level ozone.

Sources of Carbon Monoxide. Incomplete combustion generates CO. The major global sources of CO are biomass burning (e.g., vegetation fire emissions) and vehicle exhaust created from fuel burning. Other sources include burning carbon-containing fuels like wood, coal, natural gas, and kerosene. The incomplete combustion is more common for high surface-to-volume ratio devices such as small engines since they cause rapid quench. CO is thus generated by vehicle exhaust, small engine devices like lawnmowers, and heating systems such as fireplaces, oil burners, and fire. Industrial processes, solid waste burning processes, and smoking tobacco also release CO.

Impact of Carbon Monoxide on Health. When CO enters the bloodstream, it replaces oxygen in the red cells, reduces the amount of oxygen delivered to essential organs (e.g. heart and brain), which cause severe tissue damage, dizziness, confusion, chest pain, and blurred vision. Exposure to a significantly high-level of CO can even lead to a loss of consciousness and death. When the CO concentration is low in the ambient air with a low level of exposure, if exposed for a prolonged time, it can also result in neurological damage. For people with underlying health complications, short-term exposure to CO can lead to angina that causes chest pain from a reduced amount of oxygen in the blood.

Box 2.2. How to Prevent Carbon Monoxide Poisoning?

- Install a carbon monoxide detector in an indoor environment (e.g. garage, home, restaurant, etc.)
- Receive a regular (e.g. annual) check-up on the carbon monoxide detector from a technician
- Do not leave operating motor vehicle inside a confined area (e.g. garage) for a prolonged time
- Never operate gasoline-powered engines in the confined area (e.g. garage, basement, or enclosed place)
- Keep debris off the ventilation line as it can interfere with the ventilation process

Ground-level Ozone (O_3)

Definition and Properties of Ozone. O_3 is a highly reactive gas in the atmosphere composed of three oxygen atoms. Its color varies from transparent to light blue. There are two types of ozone, which are stratospheric O_3 and tropospheric (ground-level) O_3. Stratospheric O_3 is "good" ozone and ground-level O_3 is "bad" ozone. The stratospheric ozone layer in the stratosphere is beneficial to human health by serving as a shield through absorbing ultraviolet (UV) radiation, which is detrimental to people's health. However, the ground-level O_3 in the troposphere is harmful as it readily reacts with other molecules in the atmosphere and hurts people's health and ecosystem. The ground-level O_3 is an important constituent of smog along with PM. The lifetime of O_3 is on the order of several weeks, which allows long-range transport of this air pollutant.

Source: National Oceanic and Atmospheric Administration (NOAA), USA

Sources of Ground-level Ozone. Ground-level O_3 is classified as a secondary air pollutant. It is formed through a complex photochemical reaction among CO, NMVOC, NO_X, CH_4, and sunlight. The ground-level O_3 concentration is particularly higher during the hot summer season as sunlight plays a vital role in driving the O_3 formation. Its concentration peaks in the middle to late afternoon of a day when the sunlight is the most intensive. Such a formation mechanism of ground-level O_3 makes it more difficult to control compared to other primary air pollutants as its control requires collective control measures on its precursors such as VOCs and NO_X.

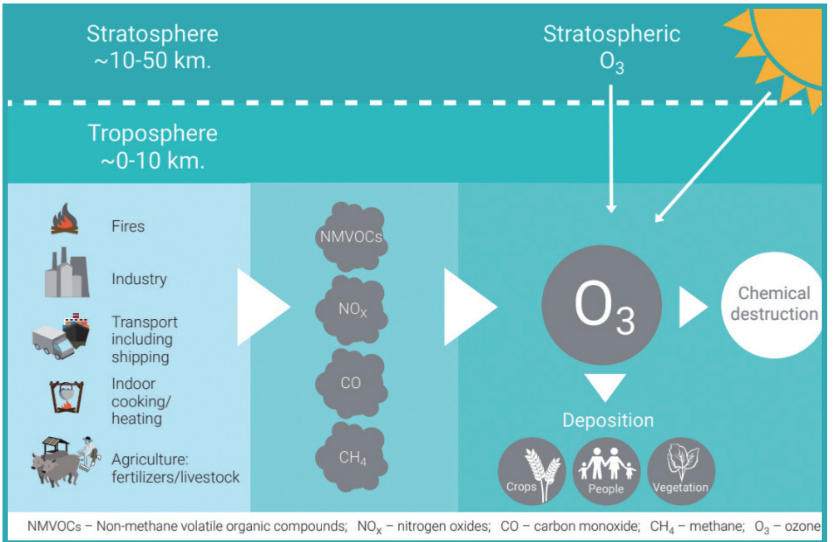
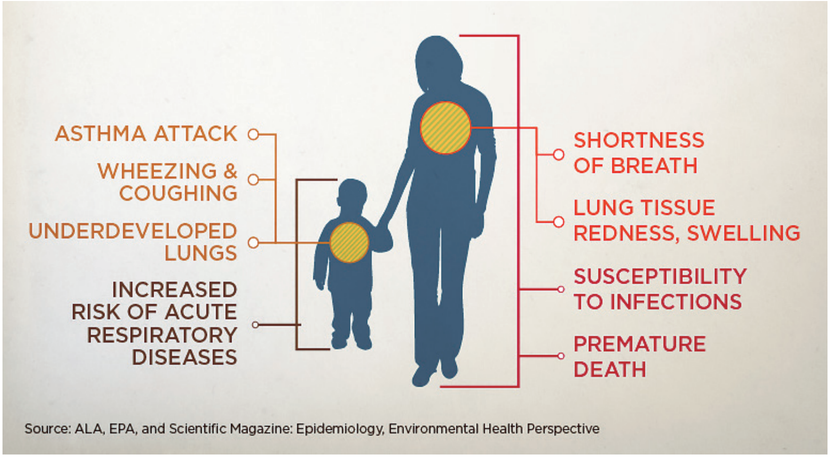


FIGURE 2: SOURCES OF GROUND-LEVEL OZONE

Source: UNEP, 2019

Impacts of Ground-level Ozone on the Ecosystem. Ground-level O_3 is a highly reactive and active oxidizing agent that harms vegetation and the ecosystem as a whole. It affects an agricultural yield by injuring the horticultural crops visibly, thereby incurring economic loss for farmers. It can harm local crops by causing reddening and necrosis, a cell injury that can ultimately kill the living tissue. Furthermore, ground-level O_3 not only reduces the photosynthesis rate but also terminates the growth and accelerates the leaf aging of crop species that further reduces crop yield. Ground-level O_3 can also influence the vitality and health of the forest. It can cause visible leaves-related symptoms and decline the growth of plants through interference with the photosynthesis process. Such detrimental effects on individual plants can lead to the biodiversity of the ecosystem. Additionally, ground-level O_3 can disturb plants' uptake of atmospheric carbon or a process known as "carbon fixation," which is a method of converting inorganic carbon to organic carbon that can act as a building block for essential activities.

Impacts of Ground-level Ozone on Health. When a person breathes in O_3, it tightens the airway muscle, which can lead to immediate difficulty in breathing and make people wheeze and cough. For people with underlying lung diseases, ground-level O_3 can trigger aggravated asthma and chronic obstructive pulmonary disease (COPD), which can lead to hospital admittance. It also increases susceptibility to respiratory inflammation and pulmonary infections. Exposure to ground-level O_3 for longer than eight hours (e.g. days, months, and years) has more serious health implications for different age groups. While it decreases lung functionality among newborn babies, it increases the chance of developing asthma among children. Lastly, for any age group, chronic exposure to O_3 can lead to premature death.



Sources: ALA, EPA, and Scientific Magazine: Epidemiology, Environmental Health Perspective

Nitrogen Oxides (NO_x)

Definition and Properties of Nitrogen Oxides. NO_x is a group of compounds that is toxic, irritating, and highly reactive with other molecules that exist in the atmosphere. Nitric oxide (NO) and nitrogen dioxide (NO_2) constitute a NO_x family ($NO_x = NO + NO_2$). NO, and NO_2 cycle between each other when ozone is present within a minute through a chemical reaction during the day. For instance, NO reacts to O_3, which creates NO_2. NO_2 is typically used as an indicator of NO_x as it causes more health complications than NO. NO is colorless and NO_2 exhibits red to brown color with a pungent smell. Although NO_x itself is a primary pollutant, it is a major ingredient of two important secondary pollutants, namely ground-level O_3 and secondary PM. The formation of O_3 entails the breakdown of NO_2 with UV light, which yields NO and oxygen atom (O). O_3 is generated following the reaction of oxygen atom with atmospheric oxygen (O_2). The lifetime of NO_x ranges from hours to days, and its lifetime depends on the concentration of hydroxyl radical (OH) and photolysis rate since the formation of nitric acid (HNO_3) through the reaction of OH with NO_2 is the most common removal mechanism of NO_x in the atmosphere.

Sources of Nitrogen Oxides. NO_x predominantly originates from anthropogenic sources and is emitted by high-temperature combustion such as during fuel burning (e.g. gas, oil, coal, etc.). In tropical regions, biomass burning also emits a high level of NO_x. In urban areas, the single greatest source of NO_x is from the transportation sector (e.g. automobiles, aircraft, ships). There are also natural sources of NO_x, including atmospheric lightning, biological activities (i.e. nitrogen cycling) in soil, and a chemical process that converts NH_3 to NO_x. The greatest sources of soil emission are the regions with heavily applied nitrogen fertilizer for agricultural purposes.

Source: UNICEF/Mungunkhishig Batbaatar

Impacts of Nitrogen Oxides on the Ecosystem. NO_x can transform into nitrate aerosols in the atmosphere via a series of chemical reactions. Such nitrate aerosol increases the aerosol uptake of water and aerosol's ability to scatter light that creates a haze event, obscuring a clear view of the sky. NO_x is a major ingredient of photochemical smog with VOC and sunlight, which also decreases people's welfare. Once NO_x is released into the atmosphere, it easily reacts with water to form nitric acid. Nitric acid can mix with water and snow into acid rain to precipitate. The transformation of NO_x to nitrate can induce nutrient over-enrichment in the aquatic environment, which is known as "eutrophication." When an excess nutrient is available in an aquatic system, it triggers the blooming of plants and algae and hypoxia (i.e. oxygen depletion), creating unfavorable living conditions for marine animals.

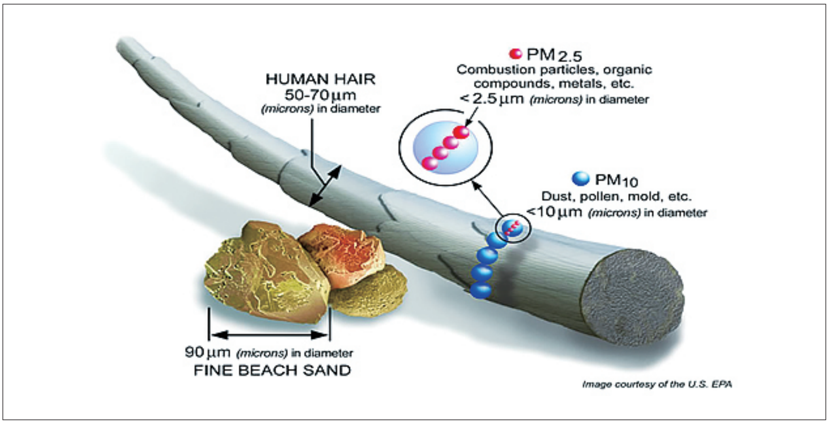
Impacts of Nitrogen Oxides on Health. NO_2 is mainly associated with a high risk of respiratory problems. Once NO_2 penetrates through the lung, it inflames the organ and decreases immunity, which triggers symptoms like bronchitis, coughing, flu, and cold. NO_2 can be fatal for people with asthma and COPD as it sets off to a more intense asthma attack. Prolonged exposure to NO_2 can also increase the likelihood of developing asthma, especially for children since they have a faster breathing rate for body weight compared to adults. Other studies indicate that infants and children who are exposed to NO_2 for a long time can have smaller lungs when they reach maturity than those who did not.

Box 2.3. Definitions of Aerosols, Particles, Haze, and Smog

- Aerosols: Tiny particles dispersed/suspended in a gaseous environment.
- Particle: An aerosol particle may consist of a single continuous unit of solid or liquid containing many molecules held together by intermolecular forces and primarily larger than molecular dimensions (>0.001 μm); a particle may also consist of two or more such unit structures held together by interparticle adhesive forces such that it behaves as a single unit in suspension or on deposit.
- Haze: An aerosol that impedes vision and may consist of a combination of water droplets, pollutants, and dust; The particle diameter is less than 1 μm.
- Smog: A term derived from smoke and fog, applied to extensive contamination by aerosols; now sometimes used loosely for any contamination of the air.

Source: Seinfeld and Pandis, 2016

Particulate Matter (PM)



Source: US EPA

Definition and Properties of Particulate Matter. PM refers to a suspended solid or liquid in gas. It can be both primary and secondary pollutants. The primary PM consists of a mixture of organic, inorganic salts, mineral dust, and black carbon. The common constituents of the secondary PM include organic and inorganic compounds (e.g. sulfate, nitrate, ammonium, and chloride), with varying compositions, depending on whether it is in an urban or rural location. PM can be classified as PM_{10} and $PM_{2.5}$ depending on the size. PM_{10} are particles, with diameters smaller or equal to 10 micrometers, and $PM_{2.5}$ are fine particles, with diameters smaller or equal to 2.5 micrometers. As $PM_{2.5}$ penetrates through the lung more effectively than PM_{10}, they pose a greater threat to public health. The global population-weighted $PM_{2.5}$ is composed about 30% from inorganic compounds, mainly of sulfate-nitrate-ammonium (SNA), 32% of organic mass, and 38% from primary components such as black carbon, mineral dust, and sea salt. This indicates that about two thirds of $PM_{2.5}$ is composed of secondary pollutants, while the rest is from primary pollutants. Depending on the proportion, meteorological condition, and development condition of location's precursor gases (e.g. SOx, NOx, NH_3), $PM_{2.5}$ composition varies, requiring a different tackling strategy for each region.

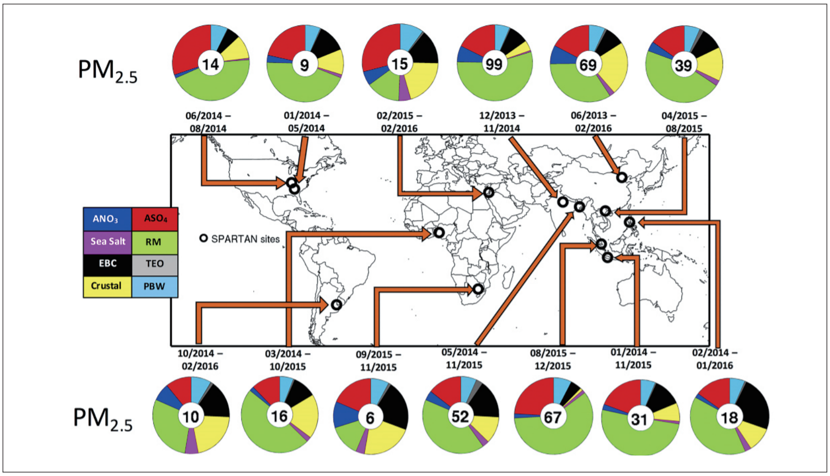
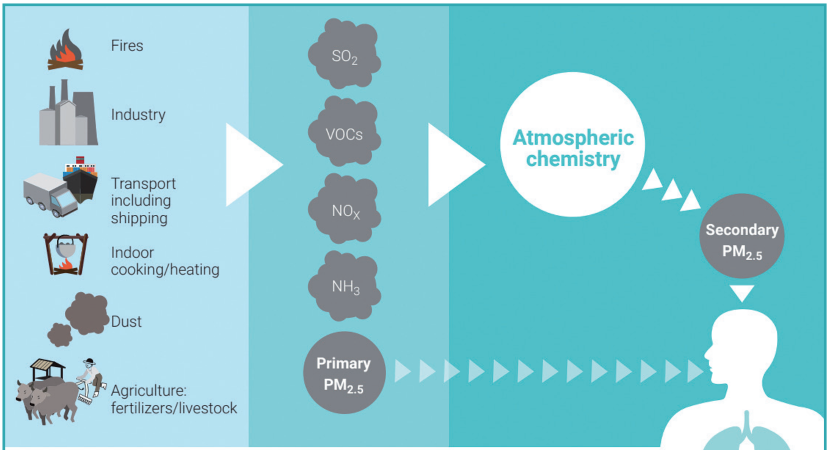


Figure 2.1. Global $PM_{2.5}$ Composition. [Source: Modified from *Figure 2. $PM_{2.5}$ Mass (inner circle, $\mu g\ m^{-3}$) and Composition Mass Fraction (filled colours)* in Graydon Snider et al. (2016). Variation in Global Chemical Composition of $PM_{2.5}$: Emerging Results from SPARTAN.]

Sources of Particulate Matter. There are both natural and anthropogenic sources of PM. The sources of primary particulate matter include dust from roadways or construction sites, forest wildfire, sea spray, and volcanic eruption. They are emitted directly into the atmosphere. On the other hand, the formation of secondary PM requires precursors such as NH_3, SO_x, NO_x, and VOCs. These precursors go through a series of chemical reactions to create secondary particulate matters. They are emitted from industry (e.g. combustion), transportation sector (e.g. automobile, aircraft, ship), residential sector (e.g. heating, cooking, personal care products, cleaning products), as well as the agricultural sector (e.g. N fertilizer, animal manure). It is more difficult to control the secondary particulate matter than the primary particulate matter as it requires holistic control measures to keep precursors at low levels.



SO_2 – sulphur dioxide; VOCs – volatile organic compounds; NO_X – nitrogen oxides; NH_3 – ammonia; $PM_{2.5}$ – particulate matter with an aerodynamic diameter equal to or less than 2.5 micrometres (μm)

Primary inorganic and organic $PM_{2.5}$ particles are those released directly to the atmosphere and inhaled by the population; these include dust from roads and black carbon from combustion sources. Secondary inorganic and organic $PM_{2.5}$ particles, on the other hand, are formed in the atmosphere from chemical reactions involving primary gaseous emissions: nitrogen oxides and sulphur dioxide mainly from cities and industrial areas; ammonia mainly from agricultural sources; and volatile organic compounds from solvent use. Because of their small size, both primary and secondary particles can be transported over large distances.

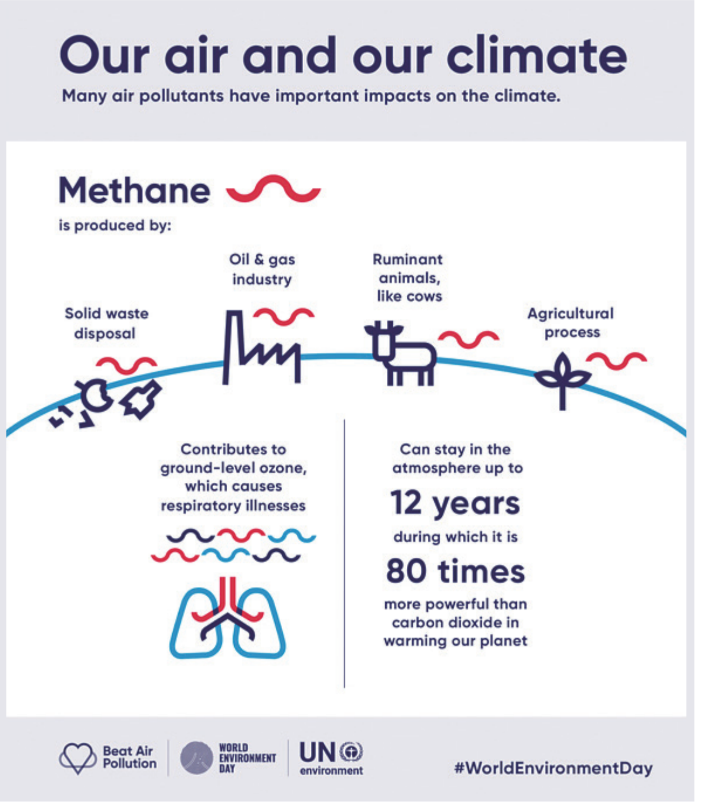
FIGURE 1: SOURCES AND COMPOSITION OF $PM_{2.5}$

Source: UNEP

Impact of Particulate Matter on Health. $PM_{2.5}$ can cause airway damage. Once inhaled, $PM_{2.5}$ deposits pulmonary alveoli and enters the lung cells. Then it induces oxidative stress onto the cell, impairing or even killing the cell. This can lead to inflammation of the airway and a decline in lung functionality. Also, chronic exposure to $PM_{2.5}$ puts excessive oxidative stress on lung cells that can increase the susceptibility to lung infection, leading to the development of asthma, chronic bronchitis, and COPD. Prolonged exposure can ultimately increase the risk of lung cancer. Indeed, PM was categorized as a carcinogen for lung cancer by the WHO's International Agency for Research on Cancer (IARC) in 2013. Moreover, $PM_{2.5}$ can exert oxidative stress on the central nervous system, particularly the hypothalamus, which can damage the cardiac autonomic nervous system and lead to abnormal heart rate variability. Such dysfunction in heart rate variability can also increase the risk of cardiovascular diseases. There is evidence that $PM_{2.5}$ is especially detrimental to infants by triggering premature births and lower birth weight.

Volatile Organic Compounds (VOCs): Methane (CH_4) and Non-methane Volatile Organic Compounds (NMVOCs)

Definition of the Properties of Methane. CH_4 is an odorless, colorless, and flammable gas that is a plentiful form of hydrocarbon found in the atmosphere. It is a greenhouse gas that is involved in the formation of ground-level O_3. It exhibits a continuously increasing trend with an annual growth rate of 6 ppb yr^{-1}. The CH_4 is removed from the atmosphere by reacting with hydroxyl radical (OH).

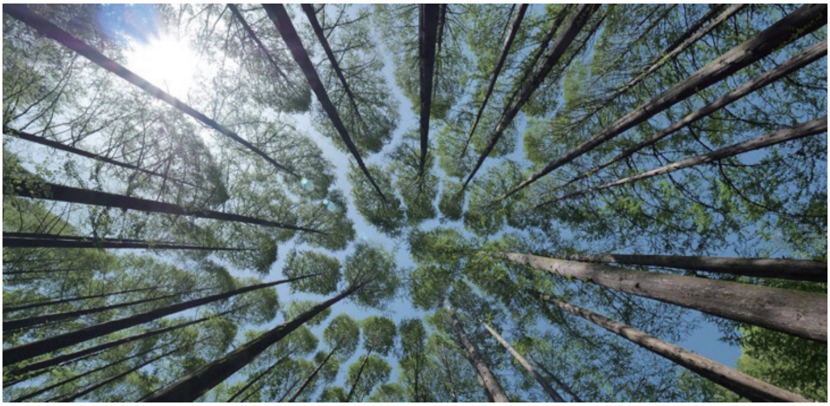


Source: UNEP

Sources of Methane. About two-thirds of the CH_4 emission is attributable to anthropogenic activities and the rest are from natural sources. The largest natural source of CH_4 is natural wetlands. Anthropogenic sources of methane include agricultural activities such as rice paddies, and domestic animals' enteric fermentation (a digestive process of breaking down intake food and releasing carbon dioxide (CO_2) and methane), biomass burning, solid waste removal, and fossil fuel production. Agricultural activity is the single greatest contributor to the anthropogenic sources of CH_4.

Definition of Non-Methane Volatile Organic Compounds. NMVOCs are carbon-based compounds with high vapor pressure that evaporates easily at room temperature, excluding CO, CO_2, and CH_4. NMVOCs have a distinctive odor depending on the sources like the smell of gasoline, alcohol, or fresh paint. NMVOCs are also a key material needed for the O_3 formation along with NO_x and they contribute to the formation of secondary PM.

Sources of Non-Methane Volatile Organic Compounds. About 90% of the NMVOC emission is biogenic, and only the remaining 10% is anthropogenic. As terrestrial vegetation is the single greatest source of NMVOCs globally, trees constantly emit VOCs (i.e. isoprene and terpenes) during the process of photosynthesis. Anthropogenic sources include paint, adhesives, carpets, cosmetics, fragrances, deodorants, cleaning products, biocides, paints, refrigerant, usage of fossil fuel, and biomass burning.



Source: UNEP

Impact of Non-Methane Volatile Organic Compounds on Health. NMVOCs affect the senses (i.e. disturbing odor) and irritation in eyes. Constant exposure to NMVOCs can lead to breathlessness and a reduction in lung functionality. Another set of studies found that long-term exposure can lead to a malfunction in the central nervous system. In the case of toxic VOCs (i.e. formaldehyde from tobacco smoke), they can cause cancer.

Sulfur Oxides (SO_x)

Definition and Properties of Sulfur Oxides. SO_x are a group of compounds that are composed of sulfur and oxygen. They are a highly soluble colorless gas with a distinctive pungent smell and taste. The most commonly used indicator for SO_x family is sulfur dioxide (SO_2), which has an average lifetime of 2 days in the ambient air and can transform into other forms of SO_x family through a series of chemical reactions. Although SO_x itself is a primary pollutant, it also acts as a precursor to secondary PM by forming sulfate particles through chemical reactions with other compounds.

Sources of Sulfur Oxides. The largest anthropogenic source of SO_2 emissions is fossil fuel combustion. The stationary fuel combustion, such as coal combustion in power plants, is the single greatest source of SO_2. The SO_2 emission from fuel-burning differs depending on the percentage of sulfur content in fuel, and coal has high content of sulfur as compared to natural gas, gasoline, or oil. Since the major source is the stationary source, it is easier to control sulfur oxides emission as compared to other air pollutants. Other smaller sources of SO_2 include the transportation sector (e.g. ship, automobile, truck). There are also natural sources of SO_2 like bacterial activity in the soil and volcanic eruption.

Source: UNEP

Impact of Sulfur Oxides on the Ecosystem. Exposure to a high concentration of SO_2 is detrimental to vegetation. SO_2 first enters the foliage through the stomata, a gas exchange site for plants. The plant rapidly absorbs SO_2 through stomata and the accumulation of sulfite (SO_3^{2-}) takes place. This sulfite compound then interferes with the plant's essential metabolic processes causing injury to the plant. Also, SO_2 is known to decrease the photosynthesis rate of plants, hindering the growth of the plant. Similar to NO_2, SO_2 is an important ingredient in acid rain. In the atmosphere, SO_2 goes through a chemical reaction and forms sulfuric acid which forms acidic precipitation. Furthermore, SO_2 forms sulfate particles that can form a hazy environment, obscuring one's visibility.

Impact of Sulfur Oxides on Health. Even a short-term exposure (10 minutes) to the elevated level of SO_2 can be an irritant for eyes, nose, throat, and airway, causing people to cough, wheeze, and feel discomfort while breathing with tightness in the chest. Also, asthmatic individuals can experience an exacerbated asthma attack. SO_2 is mainly associated with respiratory (e.g. asthma and COPD) and cardiovascular complications. In addition, SOx can transform to sulfate through chemical reactions in the atmosphere, which becomes an important constituent of $PM_{2.5}$ that causes more health complications related to the penetration of fine particulate matter.

Chapter 3

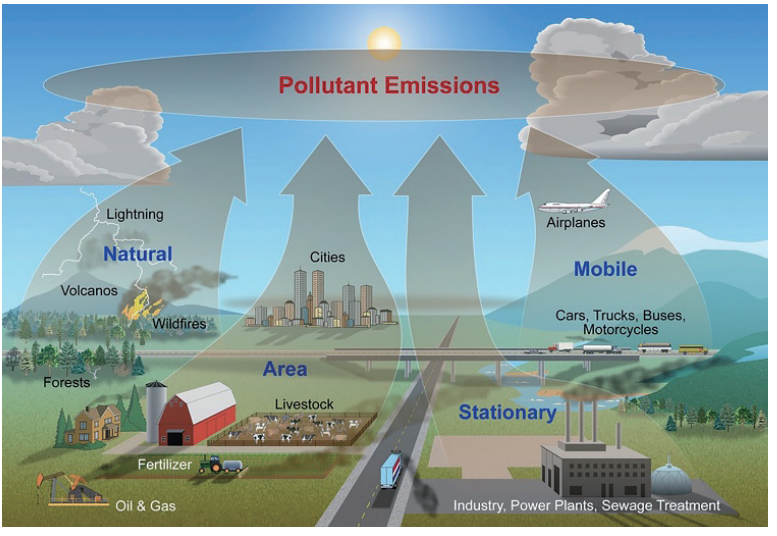
Factors Responsible for Air Pollution: What Causes Air Pollution?

1. Natural Sources
2. Mobile Sources
3. Stationary Sources
4. Area Sources

Chapter 3

Factors Responsible for Air Pollution: What Causes Air Pollution?

Air pollution can be broadly categorized into the following four sources depending on where it is emitted: natural, mobile, stationary, and area sources.



Sources: National Park Service, US Department of the Interior

1 Natural Sources

Overview of Natural Sources. Natural sources of air pollution are generated naturally instead of being attributed to human activity. Examples of natural sources include suspended dust, sea spray, forest fires, volcanic eruption, bacterial activity, lightening, and vegetation.

Source: UN News

Emission of Natural Sources.

- CO: The oxidation process of CH_4 and NMVOC takes place in the atmosphere, and they form CO in the atmosphere. Also, volcanic activity and wildfire emit carbon monoxide as they entail incomplete combustion.

- GHGs: About one-third of CH_4 is from a natural source like emission from the natural wetlands. Volcanic activity also emits CO_2 from the erupted and unerupted magma. About 0.26 gigatons of CO_2 are emitted from volcanic activity as compared to 35 gigatons of CO_2, which are emitted from anthropogenic activity. Wildfire emits a wide-range of GHGs (e.g. CO_2, CH_4, N_2O) from the incomplete combustion of vegetation and as a by-product of combustion.

- NO_X: Lightning forms NO in the atmosphere as it undergoes a rapid temperature change from hot to cold forming NO from N_2 and O_2. It accounts for about 10% of the global NO_X budget. NO then converts to NO_2 through oxidation in the atmosphere. Another important natural source of NO_X is soil microbial processes, which are accountable for about 25% of global NO_X emission. Microbes in soil undergo nitrification and denitrification processes, both of which release NO as a by-product.

- NMVOCs: NMVOCs play an important role in photochemistry as one of the ingredients to form tropospheric O_3. Natural emission from vegetation is the single largest emitter of NMVOCs. Biogenic emissions (e.g. woods, crops, and shrub) account for 90% of the total NMVOC emission globally. Among NMVOCs, isoprene is the greatest emission rate that is released during the photosynthesis process of mostly deciduous vegetation. An increase in temperature also triggers more isoprene emissions. Another important NMVOC is monoterpenes, which are emitted throughout the day and night from plants.

- PM: Natural sources generate both primary and secondary PM. Primary sources include mineral dust from wind erosion and sea spray, which are directly ejected from the ocean, black carbon from wildfire, sulfate aerosol formed from marine and volcanic emission, as well as organic aerosol emitted from biogenic sources like vegetation. The secondary PM includes sulfate aerosol formed from the oxidation of SO_X and nitrate aerosol generated from NO_X oxidation.

- SO_X: The single greatest natural source of SO_X is from volcanic activity.

2 Mobile Sources

Overview of Mobiles Sources. The mobile sources are defined as the emission of air pollutants from anything that "mobilizes." Mobile sources are typically divided into two sectors, namely "on-road" and "non-road." The examples of on-road are cars, trucks, buses, and motorcycles that operate on-road, while those of non-road are aircraft, trains, marine vessels, equipment used in construction, and small engines such as lawnmowers.

Source: UN Photo/Nasim Fekrat

Emission from Mobiles Sources.

- CO: CO is formed during an incomplete combustion process. Mobile sources, including both on-road (e.g. cars, trucks, buses, and motorcycles) and off-road (lawnmowers, boats, ships, aircraft), are responsible for emitting the majority of CO. According to the U.S. EPA, in urban areas, for instance, 95 percent of CO emission is attributable to vehicle exhaust.

- GHGs: According to the IPCC, the transportation sector (on-road and non-road combined) accounted for 14 percent of the 2010 global greenhouse gas emission. It is attributable to the fact that CO_2 is the major by-product of the burning of petroleum-based fuels (e.g. gasoline and diesel).

- NO_X: The combustion process of gasoline and diesel fuels in mobile sources releases NO_X to the atmosphere. In the urban city, mobile and stationary sources are responsible for the majority of NO_X emissions. Indeed, the urban-suburban has a boundary-layer NO_X mixing ratio of 10-1000 ppb, whereas the remote rural area has 0.2-10 ppb. It represents that the fossil fuel combustion process is the major source of NO_X.

- NMVOCs: A mobile source emits the NMVOCs through tailpipe emissions, refueling process, and evaporative loss process. Examples of evaporative loss processes include gasoline vapors release resulting from temperature change, hot soak, losses during running, and permeation. Among these NMVOCs include air toxics (e.g. benzene, acetaldehyde, aldehyde, butadiene, etc.).

- PM: Both primary and secondary PMs are emitted from mobile sources. The primary PM includes diesel PM that originates from diesel engine emissions and black carbon from fossil fuel combustion. NO_X and SO_X that are released to the atmosphere due to mobile sources undergo chemical reactions to form nitrate and sulfate, which constitute fine PM.

- SO_X: Mobile sources are responsible for SO_X emission as it requires the combustion of fuel for mobile objects to operate. In particular, diesel combustion emits more SO_X than gasoline (< 300ppm) by containing more sulfur content (0.1%).

3 Stationary Sources

Overview of Stationary Sources. Stationary sources refer to non-moving, point sources that emit a significant amount of air pollution from one location. Examples of stationary sources include power stations, oil refineries, boilers, and industrial plants.

Source: UN

Emission from Stationary Sources.

- CO: As the incomplete combustion of carbon fuel emits CO, power plants (e.g. coal-, gas-, and oil-fired) are the key source of CO emission. Other industrial processes, including petroleum refinery, metal production, and chemical production, also emit CO.

- GHGs: According to the IPCC, the industry (e.g. burning of fossil fuels at facilities), production of electricity and heat (e.g. coal, natural gas, and oil burning), and other energy production processes (e.g. refining, processing, and transporting of energy) combined accounted for 56% of the global greenhouse gas emission in 2010. The production of electricity and heat is the single largest contributor to GHGs emissions by accounting for 25%.

- NO_X: Fuel combustion in stationary sources accounts for the greatest portion of NO_X emission. There are two mechanisms in which NO_X is produced in the combustion process, namely fuel NO_X and thermal

NO_X. Fuel NO_X is caused when nitrogen in fuel is burnt and thermal NO_X is attributable to the high-temperature oxidation process that converts the atmospheric N_2 to NO_X.

- NMVOCs: NMVOCs are disposed from various means, including solvent use (e.g. dry cleaning, painting, metal degreasing, printing industry, glues, and adhesives industry, wood preservation, industrial use of solvents), chemical industry (e.g. inorganic and organic chemical industries), refineries (processes), fuel extraction and distribution (e.g. extraction, loading and distribution of gaseous or liquid fuels), gasoline distribution (e.g. service stations, storage, transporting, depositing), stationary combustion (e.g. power and industrial combustion), as well as waste treatment and disposal of other industrial sources. Some of these sources release toxic air such as benzene, propanol, formaldehyde, which put public health in a vulnerable position.

- PM: Combustion of fossil fuel from stationary sources emits black carbon and organic aerosol. Moreover, the oxidation of NO_X and SO_X forms nitrate and sulfate aerosol species that can constitute secondary PM.

- SO_X: Fossil fuel combustion is a major contributor to SO_X. Of the fossil fuel combustion, about 90% is originated from the burning of coal in a stationary source (e.g. power plants and kilns). Compared to natural gas (trace amount) and oil (0.1-1%), coal (0.5-4%) contains significantly high sulfur content, which emits a greater amount of SO_X.

4 Area Sources

Overview of Area Sources. An individual area source emits a smaller amount of air pollution at a height closer to the ground than stationary sources. It should be noted that collectively, area sources generate a significant amount of air pollution, which plays a key role in determining the local air quality. Area sources of air pollution can be exemplified by road traffic, household or building heating, agricultural activities. Air pollution can also be generated from daily lives such as solvent use, pesticide use, domestic heating, and cooking.

Emission from Area Sources.

- NH_3: Agricultural sector is the single greatest source of NH_3. Animal manure and NH_3-based fertilizers, in particular, emit a considerable amount of ammonia.

- CO: Road traffic is a major source of CO in the ambient air. The cooking and burning fuel at household/building that entails combustion at high-temperature also releases CO.

- GHGs: According to the IPCC, buildings, agriculture, forestry, and other land use account for 30 percent of GHGs emissions in 2010. The building emission includes fuel-burning for heating and cooking for domestic usage. The agricultural, forestry and other land-use sectors include raising livestock and deforestation.

- NO_X: Area sources of NO_X include road traffic and residential oil and gas combustion used for heating and cooking appliances. Also, in the areas where N fertilizer is heavily used for agricultural purposes, the soil emits significant NO_X to the atmosphere. For instance, in the California Central Valley region where substantial agriculture activity takes place, agriculture is the major source of NO_X.

- NMVOCs: Everyday lives lead to the emission of NMVOCs. Area sources of NMVOCs include light industries such as nail salons, dry cleaning agents, personal care products, cleaning products, furnishings, adhesives, domestic painting, printing, and cooking activity.

- PM: Paved and unpaved roads generate primary PM. Secondary PM can be also formed by sulfate, nitrate, and ammonium, which are created during the oxidation processes of SO_X, NO_X, and NH_3.

- SO_X: SO_X is emitted from household fuel combustion for heating and cooking as commonly used fuel contains sulfur.

Chapter 4

Effects of Air Pollution. What Are the Consequences?

1 Effects on Health

2 Effects on Agriculture

3 Effects on Environment

4 Effects on Economy

5 Long-term Effects on the Planet

6 Effects on Sustainable Development Goals

Chapter 4

Effects of Air Pollution. What Are the Consequences?

1 Effects on Health

According to the Institute for Health Metrics and Evaluation (IHME), outdoor and indoor air pollution combined was the 4th leading risk factor to the number of deaths across all age groups in 2017, causing 4.9 million premature deaths annually.

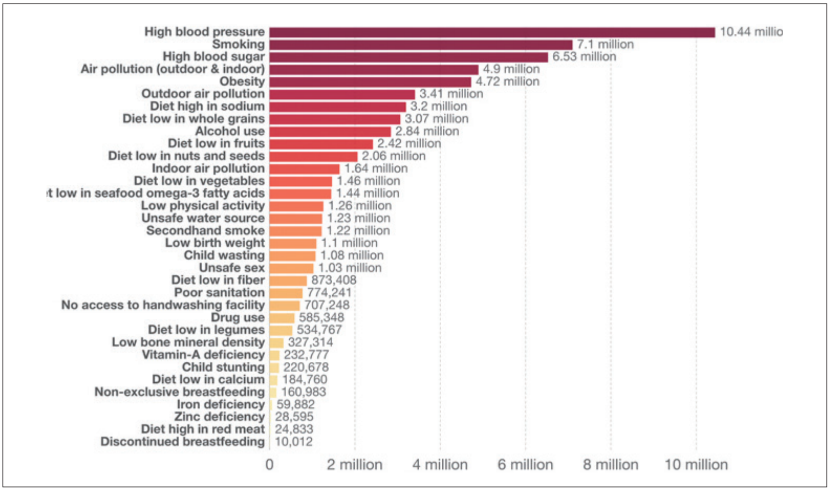


Figure 4.1. Global Number of Deaths Categorized and Ranked by Risk Factor as of 2017 as Provided by Global Burden of Diseases from IHME.
(Graph Source: Ritchie, 2018)

The estimate of WHO is slightly higher than that of the IHME. According to WHO, household air pollution accounts for some 3.8 million premature deaths and outdoor air pollution causes an estimated

4.2 million premature deaths, together accounting for 7 million deaths every year globally. Low-income and middle-income countries are more heavily affected by air pollution by accounting for 90% of 4.2 million deaths (outdoor air pollution). As children with developing lungs, people with pre-existing health complications, and the elderly are more heavily affected by air pollution than other populations, more care is needed to protect those groups of people in the event of high air pollution. The WHO also summarizes how much the proportion of each disease is attributable to outdoor air pollution.

- Lung cancer (deaths & disease): 9%
- Acute Lower respiratory infection (deaths & disease): 17%
- Stroke (deaths): 24%
- Ischemic heart disease (deaths & disease): 25%
- Chronic obstructive pulmonary disease (deaths & disease): 43%

Source: WHO

Specifically, exposure to air pollutants is known to increase admission to hospitals and the mortality rate. Depending on the exposure level and the type of air pollutant, varying short-term (e.g. nausea, skin irritation) to long-term (e.g. cancer) health complications can arise.

Table 4.1. Air Pollutants and Their Respective Health Complications

Organ	Air Pollutant	Health Complication
Respiratory System	SO_2, NO_2	• Asthma • Nose irritation, throat irritation, eye irritation • Lung inflammation: coughing, wheezing, mucous secretion • For asthmatic individuals: bronchoconstriction, dyspnea
	PM, O_3	• Asthma • Lung inflammation • Reduction in lung functionality • Lung cancer • Worse lung inflammation for individuals with pre-existing lung diseases
Cardiovascular System	CO	• Binding to hemoglobin and interfering with oxygen transfer ultimately affecting brain and heart functionality • Confusion, lack of concentration, slow reflexes
	PM	• Blood coagulation
Nervous System	PM	• Increase in ischemic stroke • Increase in stroke mortality

2 Effects on Agriculture

Food security and crop productivity are strongly linked, and previous studies have shown that air pollutants like ground-level O_3 and PM can impact crop productivity, but in different ways.

Ground-level O_3 Effect on Crop Productivity. The ground-level O_3 adversely affects crop productivity by hindering the gas exchange, inflicting damage to plant tissues, and interfering with its growth. Exposure to O_3 can lead to about 7-12 percent of the reduction in wheat, 3-5 percent of maize, and 6-16% of soy production. The sensitivity of the crop to ozone varies as wheat and soybean are more sensitive to ozone, followed by potato, rice, and maize. Barley is negligibly affected by ozone. In the case of Europe, a study in 2000 found that the ozone can incur 6.7 billion euros loss due to its negative impact on 23 crops. The level of negative effect on crop productivity is greater for countries with high levels of ground-level O_3 than those with lower levels of ground-level O_3 by requiring more stringent measures to O_3 precursors to minimize its impact.

Source: FAO/Xavier Bouan

PM Effect on Crop Productivity. Reduction in shortwave light reaching the surface and an increase in the diffuse fraction are the two competing effects of PM on the light. As PM can absorb and scatter light, it decreases the amount of shortwave light reaching the surface. However, its scattering can enhance the diffuse fraction of light. An increase in diffuse fraction helps the light to reach the lower levels of the plant, distributing the light more efficiently for plants. A previous study found that the diffuse fraction effect outweighs the incoming radiation loss, which enhances crop productivity by PM. It identified PM as increasing the production of wheat by 16.4 percent, maize by 11.5 percent, and rice by 8.9 percent.

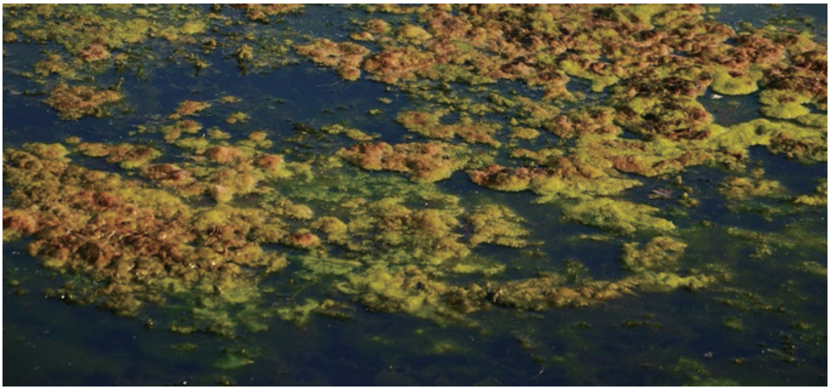
Due to such offsetting effects of O_3 and PM on crop productivity, more precautions should be taken in establishing the air pollutant control strategy for food security.

3 Effects on Environment

Acid rain. Acid rain is defined as acidic precipitation (e.g. snow, rain, or fog). It can create an acidic environment that can ultimately become uninhabitable for plants, animals, and fish. Acid rain can also influence the urban environment by making erosion of buildings or sculptures. The cause of the acid rain is air pollutants such as SO_X and NO_X, which are emitted from the burning of fossil fuel or vehicle emission. It is crucial to control the SO_X and NO_X emission to tackle the acid rain problem.

Eutrophication. Eutrophication is a phenomenon when the body of water is loaded with nutrients (e.g., phosphorus and nitrogen) which leads to the growth of plants and algae. Such a bloom of plants and algae depletes an oxygen level in water that makes the environment uninhabitable to marine species. Air pollutants can act as a source of eutrophication. For example, NO_X from mobile vehicles and industrial sources released to the atmosphere can ultimately deposit in water, causing eutrophication. Also, the manures and fertilizers containing NH_3

can induce soil acidification and the subsequent run-off to the water system can cause eutrophication.



Source: UNEP NOWPAP

Haze. Haze is a phenomenon in which the opacity of the atmosphere increases when fine solid/aqueous particles suspended in the atmosphere scatter or absorb light, which can be either white or brown. It is caused by anthropogenic activities generating air pollutants such as transportation and industry, as well as natural emission from dust or wildfires. Haze can result in the impairment of visibility, which can be dangerous for the transportation sector and also interfere with site-visits and aesthetics.

Source: WMO/Alfred Lee

4 Effects on Economy

Overview of Air Pollution Impact on Economy. According to the OECD's report on the relationship between outdoor air pollution and the economy, the global healthcare cost generated from the outdoor air pollution is predicted to reach 176 billion US dollars (USD) by 2060, compared to 21 billion USD in 2015. Also, premature deaths attributable to outdoor air pollution are predicted to be 6 to 9 million people by 2060, compared to 3 million people in 2010. About an eightfold increase in global healthcare expenditure is expected due to the global rising trend of air pollution emission from economic growth and increasing energy demand worldwide.

Market Costs Associated with Air Pollution. There are three major market costs linked to air pollution, namely health spending, labor productivity, and crop yield. Exacerbated air pollution conditions will increase hospital admission, which will increase health expenditure and decrease labor productivity. Air pollutants such as O_3 decrease the crop yield, which all have adverse impacts on the economy. The OECD expects the combined market cost from health spending, labor productivity, and crop yield to take up 1.0% of global GDP by 2060 compared to 0.3% in 2015 due to the globally increased air pollution trend.

Non-market Costs Associated with Air Pollution (Welfare Costs). The non-market costs are costs that cannot be readily observed as monetary values but affect the quality of life. The willing-to-pay (WTP) is the maximum amount of money that one will pay to procure the desired product or service, and it is used to convert the non-markets costs into monetary values. According to the OECD report ("The economic consequences of outdoor air pollution"), there are two major non-market costs associated with air pollution. The first factor is a decrease in the quality of life due to illnesses associated with air pollution such as hospital admission, pain, and inability to continue regular activity (morbidity). The OECD report predicts that the global WTP for morbidity will increase to 2.2 trillion USD by 2060, compared to 280 billion USD in 2015. The second factor is an increase in premature deaths caused by air pollution. The WTP is much higher for premature death as compared to the morbidity since the global WTP for premature death is expected to reach 18-25 trillion USD by 2060 as compared to 3.2 trillion USD in 2015. Such a six-fold to eightfold increase in WTP between those two-time frames is attributed to a projected increase in premature deaths. The OECD report used the value of statistical life (VSL) metric to calculate the WTP and adjusted each country by its income to calculate the global average WTP. More details about WTP related to air pollution can be found in the OECD report.

5 Long-term Effects on the Planet

Effects on Climate Change. The UNFCCC defines the climate change as the "change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." According to the IPCC, an expansion in GHGs since the industrial revolution has induced significant climate change and average warming of 0.85°C between 1880 and 2012.

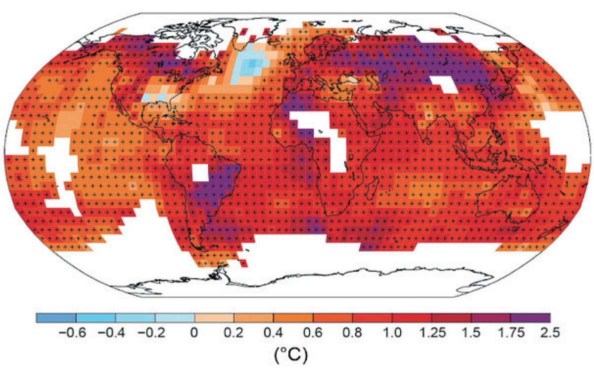


Figure 4.2. Observed Change in Surface Temperature between 1901 and 2012. [Graphic Source: IPCC (2013) WG1AR5 Figure SPM.1]

The GHGs trap the terrestrial radiation from leaving the atmosphere, which leads to higher temperatures. The IPCC categories greenhouse gases as the well-mixed greenhouse gases (e.g., CO_2, CH_4, F gases (CFCs, HFCs), and N_2O) and short-lived climate pollutants (e.g., CO, tropospheric O3, NMVOC, Black carbon and NO_X). The UNFCCC mandates countries to report emissions and removal processes for seven GHGs (i.e. CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, and NF_3) and four additional indirect greenhouse gases (i.e. CO, NMVOCs, NO_X, and SO_2).

In addition to the GHGs, aerosols and their precursors (e.g. mineral dust, sulfate, nitrate, organic carbon (OC), black carbon (BC)) play an essential role in climate change. The total aerosols present in the atmosphere also have a net cooling effect. More specifically, aerosols such as mineral dust, sulfate, nitrate, and OC cool the earth, whereas BC absorbs radiation and results in increased temperature.

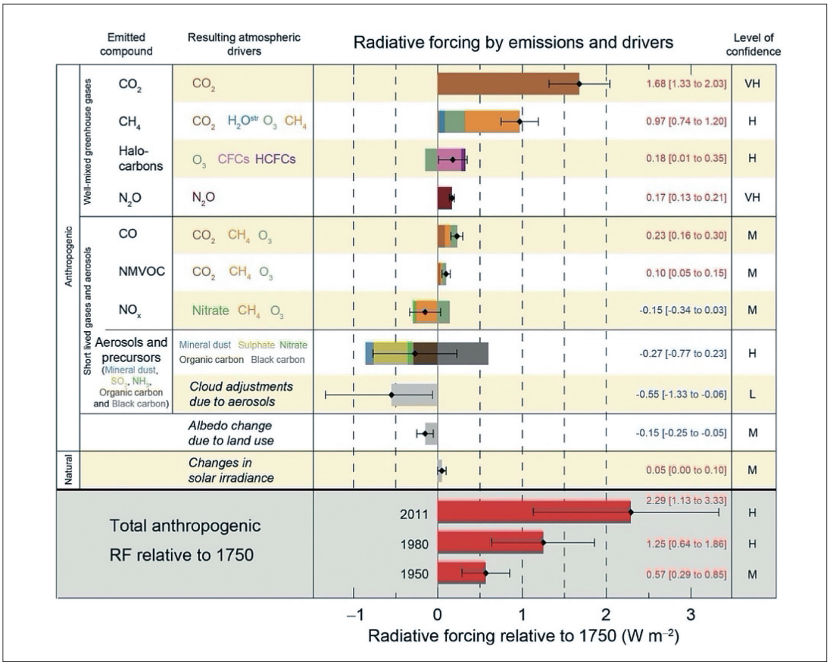


Figure 4.3. Radiative Forcing of Different Air Pollutants. (Source: IPCC)

6 Effects on Sustainable Development Goals

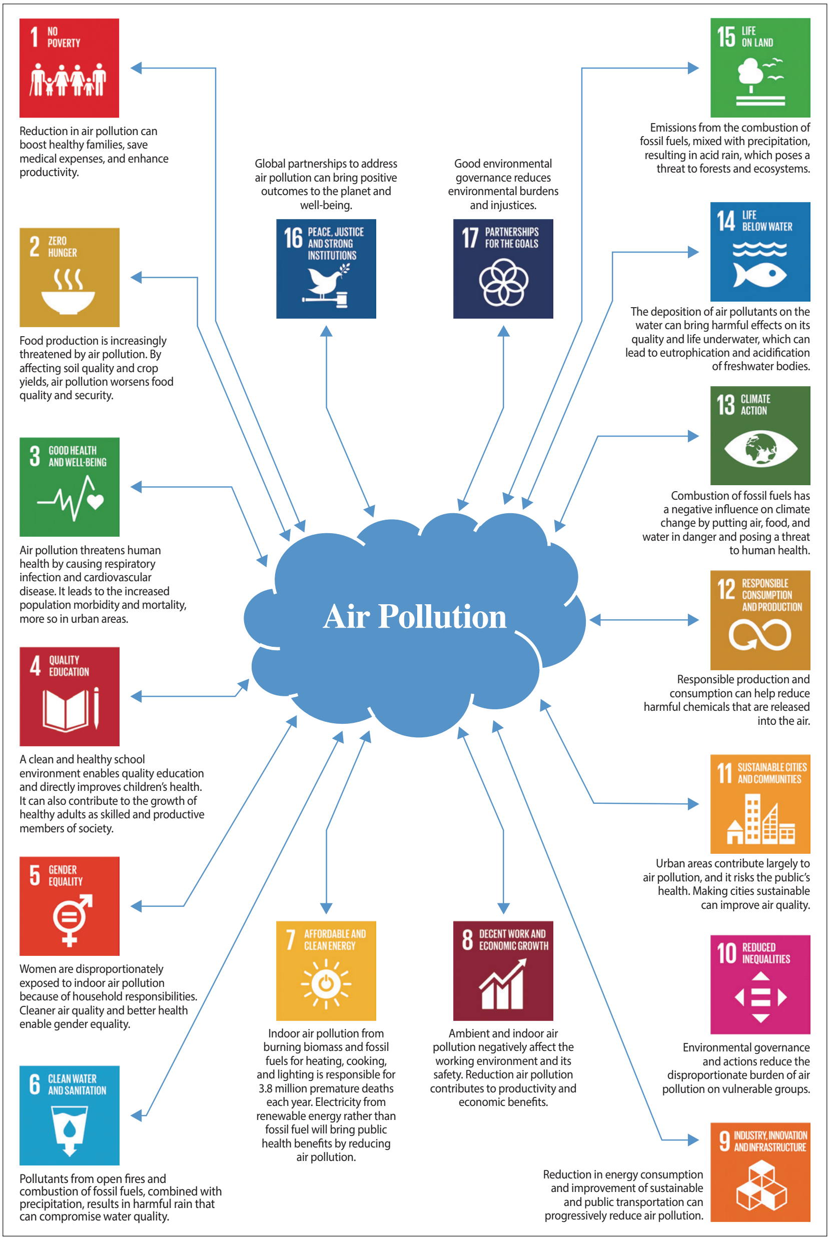


Figure 4.4. Air Pollution and SDGs

The Sustainable Development Goals (SDGs), consisting of 17 goals and 169 targets, are closely interconnected – an action in one area will influence outcomes in others. Although there is no headline Goal on air pollution in the SDGs, air pollution is closely linked to each one of them in terms of its causes and effects. For example, air pollution is derived from excess use of energy (7) and development of industry (9) and transport (11), which ultimately damages our ecosystem and brings harmful impacts on education (4), food (2), and health (3). It is important to enhance cooperation mechanisms between the air pollution and SDGs frameworks to tackle air pollution and achieve sustainable development together.

For example, the Mongolia Voluntary National Report 2019, which focuses on air pollution, analyzes the impacts of air pollution on the SDGs in terms of four different categories – health, education, income, and the environment.

Impacts on Health. In Ulaanbaatar, it is predicted that one in ten deaths is attributed to air pollution. Among the primary causes of people's morbidity are respiratory, intestinal, cardiovascular, and mental disorders at the country level. It is found that young children and youth are the most vulnerable groups, who are in danger of being left behind. The infant and under-five mortality rate linked to air pollution has also risen in Mongolia. Apart from the basic consumption expenditures such as food and housing, as many as 90 percent of all households spend 10 percent of their "other" expenditures on health services due to the increased cases of respiratory disease.

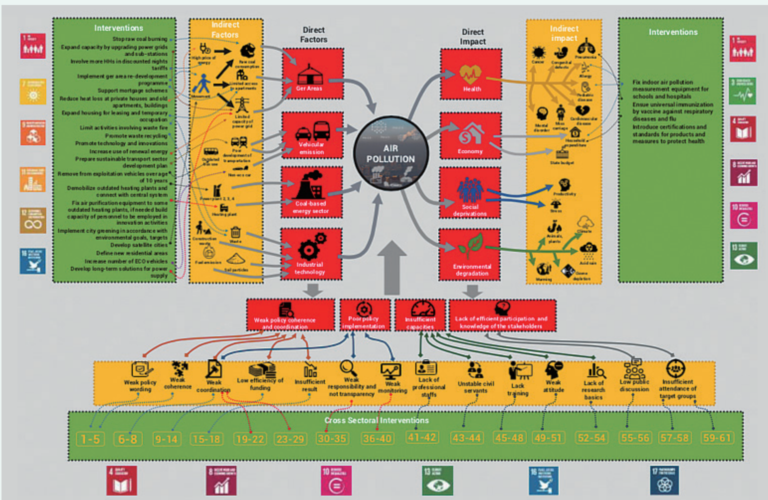
Impacts on Education. Children in Ulaanbaatar suffer from high levels of particulate matter $PM_{2.5}$ in school classrooms, which influences negatively on students' health and impairing learning. Despite some interventions, there is a need for long-lasting effect on reducing air pollution levels. It is vital to increase general awareness and knowledge on air pollution to familiarize with measures to counter or mitigate air pollution. Such awareness should be increased particularly among poorer groups and young people.

Impacts on Income. As fuel is crucial to overcome the long and harsh winters in Mongolia, it remains as a huge economic burden for Ulaanbaatar's ger households, who spend around 20 percent of their average monthly income on fuel. The cost of air pollution takes up 18 to 28 percent of the city's GDP, compared to the 8 to 13 percent of the national GDP for the entire country. To reduce indoor air pollution, public institutions also share the high cost as 75 to 78 percent of current expenditures for kindergartens is spent on heating. It is important to increase positive economic gains by opening up the economic base for Mongolia.

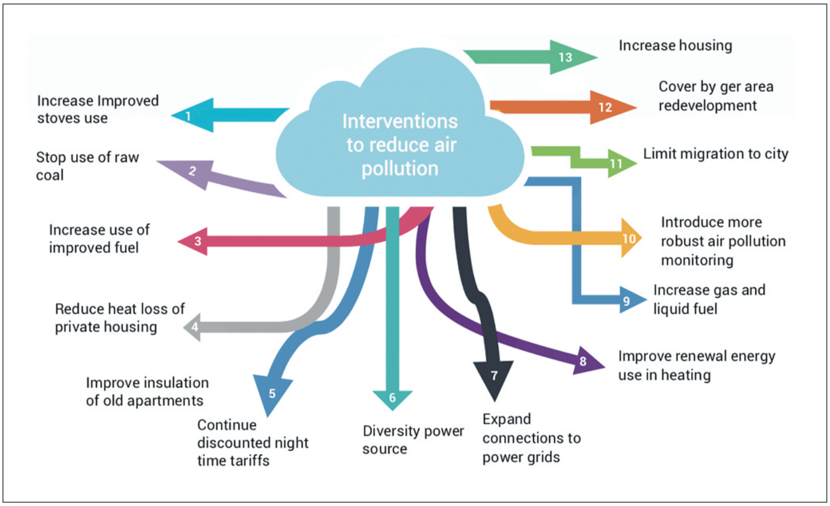
Impacts on the Environment. Despite many existing studies on air pollution, more qualitative insights on air pollution and its broader environment linkages are necessary. Mongolia is both a contributor and a victim of global warming and climate change. The Risk Index showed that the country ranked 8th among 10 countries with highest risk of being impacted by global climate change. The increased average temperature, overall decline in precipitation levels, and the frequency of natural disasters not only destroy people's livelihoods, but also lead to an adverse consequence for the society and the economy in general.

Box 4.1. Mongolia Voluntary National Report 2019

The Mongolia Voluntary National Report 2019 features the air pollution issue as "a complicated and multifaceted global problem that would benefit from cross-sectoral coordination and multi-stakeholder partnerships through a sustainable development lens" to create effective solutions. Air pollution is an increasingly urgent development challenge in Mongolia that influences public health and productivity, while incurring a significant amount of costs for the economy.



The Mongolian government has taken several actions to enhance construction standards, bring in clean technologies, and reconstruct ger areas as part of its efforts to counter air pollution. The report identifies the weak policy coherence and coordination, poor policy implementation, insufficient capacities, and a lack of efficient participation and knowledge of stakeholders as the major challenges. It broadly recommends reinforcing the consistency of policies and actions to prevent air pollution, ensuring the coordination of institutions, advancing the roles of the actors, and promoting stakeholder participation and knowledge.



Source: Mongolia Voluntary National Report 2019

Chapter 5

What is Indoor Air Pollution?

Chapter 5

What is Indoor Air Pollution?

1 Indoor Air Pollutants and Typical Sources

Source: BreatheLife

Sources of Indoor Air Pollution. In developing countries, solid fuels (i.e. biomass and coal) used for cooking and heating is the greatest source of indoor air pollution. According to WHO, about 3 billion people still rely on inefficient fuels (e.g. coal, wood, animal dung, crop waste, and open fires) to cook, and heating households. Solid fuel is any solid material that can release energy when burnt. Biomass is an organic matter such as crops, garbage, wood, agricultural residues, briquettes, and alcohol fuel. Burning of solid fuels can result in PM_{10} concentration (24-hours mean) ranging from 300 to 3,000 $\mu g/m^3$, which is far higher than WHO's air quality guideline of daily PM_{10} concentration of 50 $\mu g/m^3$. Among other sources of indoor air pollution are environmental tobacco smoke, construction materials (e.g. concrete and stone), building materials (e.g. plywood and particleboard), furnishings (e.g. carpets and draperies), adhesives, cleaning products, and personal care products (e.g. lotion and cosmetics).

Emission of Indoor Air Pollution. The combustion of solid fuels emits CO, NO_X, SO_X, PM, and harmful NMVOCs such as aldehydes and benzene. The burning of tobacco also emits CO, NO_X, air toxic like nicotine, and other harmful NMVOCs. Moreover, building materials, furnishings, and personal products, consumer products, and adhesives release unhealthy NMVOC (e.g. formaldehyde), which discharges at a higher level for newer products. Construction and building products such as tiles, pipe insulation, and concrete also contain asbestos fibers. Lastly, construction materials like concrete and stone and soil release radon, which is a radioactive particle that penetrates through people's lungs.

Source: WHO/Ajay Pillarisetti

2 Effects of Indoor Air pollution

Health Effect. Smoke from the burning of solid fuels and biomass in households poses a serious threat to people's health, especially for developing countries that use less efficient fuels. According to WHO, about 3.8 million people die prematurely from indoor air pollution generated by inefficient fuel usage (e.g. solid fuels, kerosene, coal, and biomass burning). For children under 5 years old, indoor air pollution is more fatal as half of the deaths caused by pneumonia are attributable to PM pollution from the household. The proportion of each disease among 3.8 premature million deaths is as follows:

- Pneumonia: 27%
- Stroke: 18%
- Ischaemic heart disease: 27%
- COPD: 20%
- Lung cancer: 8%

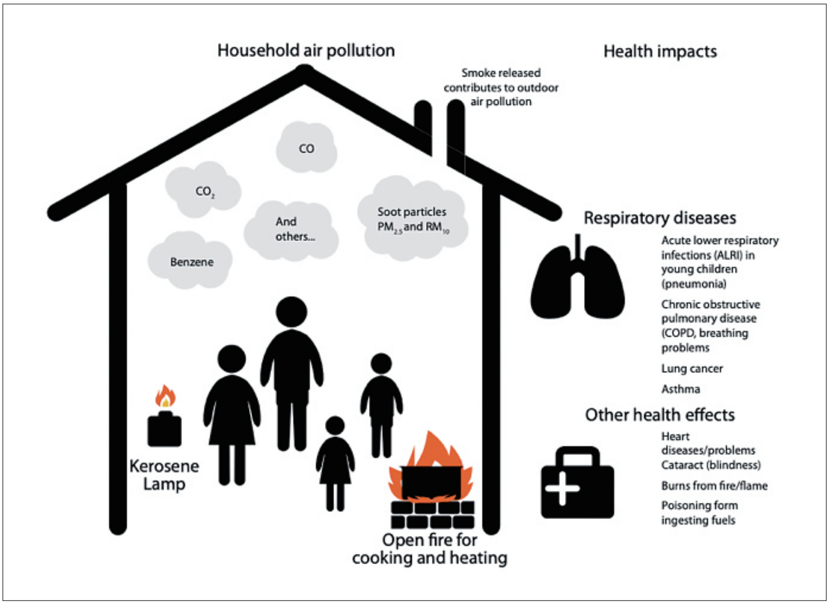


Figure 5.1. Household Air Pollution and Its Health Effects.
[Graphic Source: Towards a Pollution-Free Planet (2017)]

3 Intervention to Indoor Air Pollution

There are three interventions that can be taken to reduce exposure to indoor air pollution. First and foremost, reducing poverty in developing countries is the most effective measure to reduce indoor air pollution as indoor air pollution from the usage of solid fuel is intricately related to poverty. The implementation of the following interventions at a personal level could be difficult for low-income families calling for a need for intervention at policy-level.

Source Removal/Substitution. The first intervention method is to remove or substitute the source of air pollution. This involves substituting high pollution emitting fuel with an alternative fuel.

Usage of Alternative Fuel. One way of controlling indoor air pollution is to use alternative fuels with higher fuel efficiency such as kerosene, liquid petroleum gas (LPG), low-smoke fuels, and electricity. Substituting solid fuel with cleaner and more efficient fuel can dramatically improve the indoor air quality situation. For instance, in the rural setting of India, using kerosene for cooking resulted in exposure to particulate matter concentration of 132 $\mu g/m^3$, as opposed to particulate matter concentration as high as 1,300 $\mu g/m^3$ for using wood and 1,500 $\mu g/m^3$ for using dung. Just by substituting for cleaner fuel decreased the exposure by 10 orders of magnitude. Compared to LPG and kerosene, substitution with electricity requires the building of infrastructure, so for developing countries, LPG and kerosene are more viable options for fuel substitution.

Improvement of the Living Environment. Another way of improving indoor air pollution conditions is to modify the living environment to reduce the exposure of people indoors.

Improved Ventilation. The living conditions for people can be improved by having a design component in the building or household to allow for the recirculation of air from indoor to outdoor. This could be done by having hoods near the source of air pollution (e.g. kitchen) or building chimneys for air pollution flowing outdoors. Moreover, simply having more windows can allow such air exchange of indoor and outdoor environments.

Change of the Kitchen Design. A physical way of reducing indoor air pollution exposure is to design the household such that the kitchen is separated from the other parts of the house, so that family members outside of the kitchen are less exposed to indoor air pollution. This control strategy will not be the most effective measure for the cook. Another method of improving the kitchen design is to design the stove to come up to the waistline so that the cook can avoid the direct exposure that they will experience if they had to lean over to the fire.

Air Cleaning Devices. More mechanical solutions to air pollution exist, but this may not be financially viable for low-income households. This involves having air pollution control devices such as gas absorbers or electrostatic precipitators. A gas absorber is effective in removing hazardous gas from the environment, and electrostatic precipitators can remove fine particles from the household.

Change of User Behaviors. The last method to reduce the chance of exposure to indoor air pollution is through modifying behaviors in the household. The first method is to continue the maintenance of stoves, hoods, and chimneys to operate at optimal conditions. The second method is to physically distance children away from the source of air pollution and smoke generated from air pollution. Moreover, keeping the environment well-ventilated (e.g., opening a window and operating a hood if available) while cooking can decrease the indoor concentration of air pollutants.

Chapter 6

How is Air Pollution Assessed, Monitored, Managed, and Controlled?

1 Communication of Air Pollution Level with the Public

2 Example of AQI

3 Ambient Air Pollutants: Analysis and Measurement

4 Air Pollution Monitoring and Surveillance

5 Air Quality Management System and Process

6 WHO Air Quality Guidelines

Chapter 6

How is Air Pollution Assessed, Monitored, Managed, and Controlled?

1 Communication of Air Pollution Level with the Public

Overview of Air Quality Index. The Air Quality Index (AQI) is one of dimensionless values that exhibits the air pollution level of the day. AQI is used to communicating with the public about daily air quality so that people can make the most prudent decision about outdoor activity. It allows countries to have different names for AQI and ways of calculating AQI depending on their ambient air quality standards in each country. For instance, the AQI index for Canada, Singapore, and the Republic of Korea is called the "Air Quality Health Index (AQHI)," "Pollutant Standards Index (PSI)," and the "Comprehensive Air-Quality Index (CAI)" respectively. The commonality of these different AQIs is that they are calculated from different air pollutants that are associated with health complications, which are called "target pollutants" in this Handbook.

Target Pollutants and Values. AQI concerns air pollutants that pose a threat to public health. The target pollutants in AQI can differ in each country depending on the type of pollutants that are being regulated by national ambient air quality standards. Commonly, countries use SO_2, O_3, NO_2, CO, PM_{10}, and $PM_{2.5}$ to calculate AQI. Depending on the country, the range of AQI can vary. It is common that the higher AQI value is indicative of a higher level of air pollution.

Health Implications. AQI is generally categorized into four categories: "good," "moderate," "unhealthy," and "hazardous." Some countries divide this category further into "unhealthy for sensitive groups" and "unhealthy for everyone" as AQI value increases. Such categorization is possible as pollutants that determine AQI have direct health implications. Acute exposure to PM can cause respiratory inflammation, heart complication, and, ultimately, lung cancer. O_3 is linked to asthma and various lung complications. NO_2 is associated with a reduction in lung function and causes bronchitis for asthmatic children. In addition, SO_2 affects the respiratory system and results in irritation in the eyes and lungs.

Box 6.1. Five Ways to Limit Breathing Polluted Air

The World Health Organization (WHO) lists five different ways to restrict breathing polluted air:

1. Limit walking on busy streets during rush hour – and if you have a young child with you, try to lift them up above the level of vehicle exhausts
2. Limit spending time at specific hotspots of traffic such as cars stopped at traffic lights
3. When you're doing physical activity outdoors, try exercising in less polluted areas
4. Limit the use of cars in highly polluted days
5. Don't burn waste as the smoke results in damage to our health

Source: WHO

2 Example of AQI

US EPA's AQI. US EPA's AQI is classified into six categories with 0 being the best air quality and 500 being the worst air quality. AQI corresponding to 100 is equivalent to air quality meeting the standards of national ambient air quality. Air quality below 100 is satisfactory for public health, while above 100 is unhealthy for sensitive groups. Values above 200 are unsafe for everyone. The AQI value is calculated for all targeted pollutants (e.g. O_3, $PM_{2.5}$, PM_{10}, CO, SO_2, and NO_2) following the common equation, and the highest AQI amongst five pollutants are reported to the public.

Table 6.1. US EPA Air Quality Index

Air Quality Index		
AQI Category and Color	**Index Value**	**Description of Air Quality**
Good (Green)	0 to 50	None
Moderate (Yellow)	51 to 100	Unusually sensitive people should reduce prolonged or heavy exertion
Unhealthy for Sensitive Groups (Orange)	101-150	Sensitive groups should reduce prolonged or heavy exertion
Unhealthy (Red)	151-200	Sensitive groups should avoid prolonged or heavy exertion; general public should reduce prolonged or heavy exertion
Very Unhealthy (Purple)	201-300	Sensitive groups should avoid all physical activity outdoors; general public should avoid prolonged or heavy exertion
Hazardous (Maroon)	301-500	Everyone should avoid all physical activity outdoors

Source: US EPA, 2012

Box 6.2. How is AQI Calculated?

Adopted from the US EPA Technical Report on AQI (2018)

1. Truncate the concentration of the pollutant of interest (ozone: 3 decimal places, $PM_{2.5}$: 1 decimal place, PM_{10}: integer, CO: 1 decimal place, SO_2: integer, NO_2: integer), which becomes the truncated concentration of pollution (C_P).
2. Refer to Table A to see which category the pollutant of interest falls under and define the high and low break point concentrations, as well as corresponding AQI values (BP_{Hi}, I_{Hi}, BP_{Lo}, and I_{Lo}).
3. Calculate AQI for the pollutant of interest following the equation below.
4. Repeat this process for all pollutants of interest. The highest AQI value becomes the AQI of the day.

$$I_P = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}}(C_P - BP_{Lo}) + I_{Lo}$$

where I_p = Index for pollutant p
C_p = the truncated concentration of pollutant p
BP_{Hi} = the concentration breakpoint that is greater than or equal to C_p
BP_{Lo} = the concentration breakpoint that is less than or equal to C_p
I_{Hi} = the AQI value corresponding to BP_{Hi}
I_{Lo} = the AQI value corresponding to BP_{Lo}

Table A. Breakpoint Table for AQI

O_3 (ppm) 8-hour	O_3 (ppm) 1-hour	$PM_{2.5}$ () 24-hour	PM_{10}) 24-hour	CO (ppm) 8-hour	SO_2 (ppb) 1-hour	NO_2 (ppb) 1-hour	AQI	Category
0.000 – 0.054		0.0 – 12.0	0 - 54	0.0 - 4.4	0 - 35	0 - 53	0-50	Good
0.055-0.070	-	12.1- 35.4	55 – 154	4.5 – 9.4	36-75	54 – 100	51-100	Moderate
0.071-0.085	0.125 - 0.164	35.5 – 55.4	155 - 254	9.5 - 12.4	76 - 185	101 - 360	101-150	USG
0.086 - 0.105	0.165 - 0.204	55.5 - 150.4	255 - 354	12.5 - 15.4	(186 - 304)	361 - 649	151-200	Unhealthy
0.106 - 0.200	0.205 - 0.404	150.5 - 250.4	355 - 424	15.5 - 30.4	(305 - 604)	650 - 1249	201-300	Very unhealthy
	0.405 - 0.504	250.5 - 350.4	425 - 504	30.5 - 40.4	(605 - 804)	1250 - 1649	301-400	Hazardous
	0.505 - 0.604	350.5 - 500.4	505 - 604	40.5 - 50.4	(805 - 1004)	1650 - 2049	401-500	Hazardous

Example: Let 8-hour O_3 value be 0.0785ppm

1. Truncate the concentration to 3 decimal points (C_p= 0.078).
2. According to Table A, 0.078 falls under 0.071 – 0.085 category.

$$PB_{Hi} = 0.085, I_{Hi} = 150, PB_{Lo} = 0.071, I_{Lo} = 101$$

3. Now that all the symbols are defined, use equation above to calculate $I_{p.}$

$$\frac{150-101}{0.085-0.071}(0.078 - 0.071) + 101 = 126$$

4. AQI equal to 126 corresponds to USG (unhealthy for sensitive group), orange code.

3 Ambient Air Pollutants: Analysis and Measurement

Expressed Concentration of Measured Air Pollutants. Gaseous air pollutants (e.g. NO_x, CO, O_3, SO_2) are typically expressed as a mixing ratio like parts per million (ppm, 10^{-6}) or parts per billion (ppb, 10^{-9}). The pollutants in the particulate phase (e.g., PM_{10}, and $PM_{2.5}$) are expressed as mass concentration like micrograms per cubic meter (g/m^3). The mixing ratio such as ppm or ppb can be easily converted to mass concentration, mass per volume. It should be noted that different countries use different units for the same air pollutant. These concentration values are often converted to AQI.

Sampling Methods. There are three categories of sampling methods to measure the air pollutants in the ambient air: passive versus active sampling, integrated versus continuous monitoring, and personal versus area monitoring. Firstly, passive versus active sampling uses diffusion-based methods to collect pollutants and is commonly used for gaseous compounds collection (e.g., NO_x, O_3, NMVOC, etc.). Passive sampling requires no pump, cheaper than active sampling, and more flexible in placing as it requires no power supply. The active sampling, however, uses pumping devices that pull in air through. It is used for particle collection. Secondly, the integrated monitoring collects the pollutant of interest onto the filter or adhering material, which then can be averaged over the collection time, while the continuous monitoring measures the air pollutants and recording it instantaneously over the collection time. It is more costly and more concentrated in urban sites. Thirdly, area monitoring is the use of air monitoring equipment at given locations which is used to represent individual exposure for a population. Personal monitoring occurs when monitoring equipment is placed on an individual to estimate each individual's exposure to a given agent.

4 Air Pollution Monitoring and Surveillance

Importance of Air Pollution Monitoring and Surveillance. Air pollution monitoring refers to the process of measuring ambient air pollution data for a consistent time. Well-established ambient air quality monitoring is key to managing and improving air quality. The monitoring data provides information to the public with a warning if needed and can be used to calculate the air pollution trend in a selected region. They are also important data for modeling work. Since each type of monitoring method has its own strengths and weaknesses, the integration of different monitoring methods can lead to a more comprehensive understanding of air quality.

Monitoring Method 1: Ground-based Monitoring System.

Overview of Ground-based Monitoring System. Thousands of air quality monitoring stations are established in countries to monitor the air quality at hourly levels. Many countries continuously monitor and measure pollutants like O_3, NO_2, CO, SO_2, PM_{10}, and $PM_{2.5}$ by using ground-based monitoring stations. These monitoring stations have stationary instruments that utilize passive and active sampling.

Source: UNEP
Cost-effective monitoring device developed by EPA to track down the sources of air pollutants near the industrial area. (Source: US EPA)

Three Types of Operational Monitoring Stations. The operational stations can be broadly categorized into three types depending on what/where is being measured. The first type is near the urban and population center to monitor the ambient air quality of urban settings, industrial areas, and residential areas. The second type is roadsides to measure the vehicle's exhaust. The third type is the background station located in unpolluted areas far from the population to serve as a background measurement.

Strengths and Weaknesses of a Ground-based Monitoring System. The advantage of the ground-based monitoring stations is that they allow for the characterization and collection of a variety of pollutants at hourly levels. The limitation of the ground-based monitoring system is that the observational coverage is limited to local areas because of the coarse spatial resolution. It also requires a network of instruments to obtain regional data as one data point is a point measurement. Another limitation is that it is difficult to figure out the vertical structure because it is limited to near the surface.

Monitoring Method 2: Airborne-based Monitoring System through Deployment of Aircraft.

Overview of Airborne-based Monitoring System. Ground-based monitoring systems cannot access information about the vertical distribution of air pollutants. To overcome this, the aircraft is deployed to measure the vertical profile of different air pollutants. The sensors and inlets out of the aircraft can measure a variety of air pollutants such as SO_2, NO_x, CO, O_3, and PM.

Strengths and Weaknesses of Airborne-based Monitoring System. The aircraft measurement of air pollution provides a vertical distribution of air pollutants. However, the aircraft campaign has limited temporal coverage since it does not allow for continuous, every day-to-day measurement. The spatial coverage is limited to the aircraft pathway and the meteorological conditions have to be favorable for aircraft to be deployed.

Monitoring Method 3: Space-based Monitoring System Using Satellite Remote Sensing

Source: UN ©JAXA

Overview of Space-based Monitoring System. Another monitoring method of air pollution is the use of satellite remote sensing instruments. There are two types of satellites, which are the Low-Earth Orbit (LEO) and the Geostationary Earth Orbit (GEO) satellites. The LEO satellites allow for wider geographical coverage by moving constantly but provide less frequent observation for one location. Since the GEO satellites are fixed in one location, their spatial coverage is not as extensive as LEO. Nonetheless, it provides more data points for a fixed location. Unlike the ground-based and airborne-based monitoring systems, space-based monitoring can provide information about the global distribution of air pollutants. The measurements of aerosol properties (e.g. aerosol optical depth (AOD) and angstrom exponent (AE)) have been possible through satellite remote sensing with a limited characterization of gases. However, recent technology has made it possible to characterize O_3, NO_x, NMVOCs.

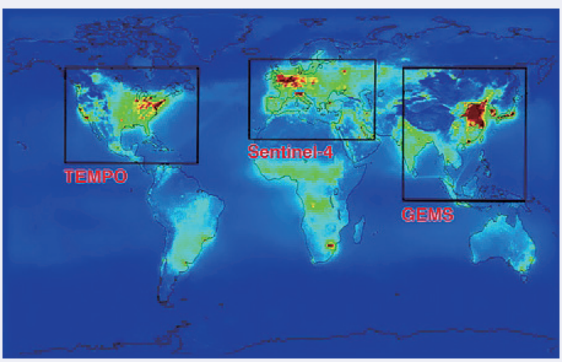
Box 6.3. **Examples of LEO and GEO Satellite Remote Sensing Instruments to Monitor Air Quality**

Moderate resolution Imaging Spectroradiometer (MODIS)

- Description: Deployed on NASA's Earth Observation System (EOS) satellites known as Terra and Aqua satellites
- Type: LEO
- Spatial Resolution/coverage: 1 km or less depending on band/global
- Temporal Resolution: A global view of the entire Earth every 1 to 2 days
- Air Pollution-related data: aerosols (e.g. AOD)

Geostationary Environment Monitoring Spectrometer (GEMS)

- Description: Deployed on the Geostationary Korea Multi-Purpose Satellite (GEO-KOMPSAT-2B) *launched in 2020 by the Republic of Korea*
- Type: GEO
- Spatial Resolution/coverage: 7km 8km for gas and 3.5 km 8km for aerosols/Asia
- Temporal Resolution: 1 hour
- Air Pollution-related data: Columnar measurement of tropospheric O_3, aerosols, NO_2, SO_2, NMVOCs (e.g. formaldehyde, glyoxal)
- Similarly, TEMPO and Sentinel-4 will be launched to monitor the U.S. and Europe respectively.



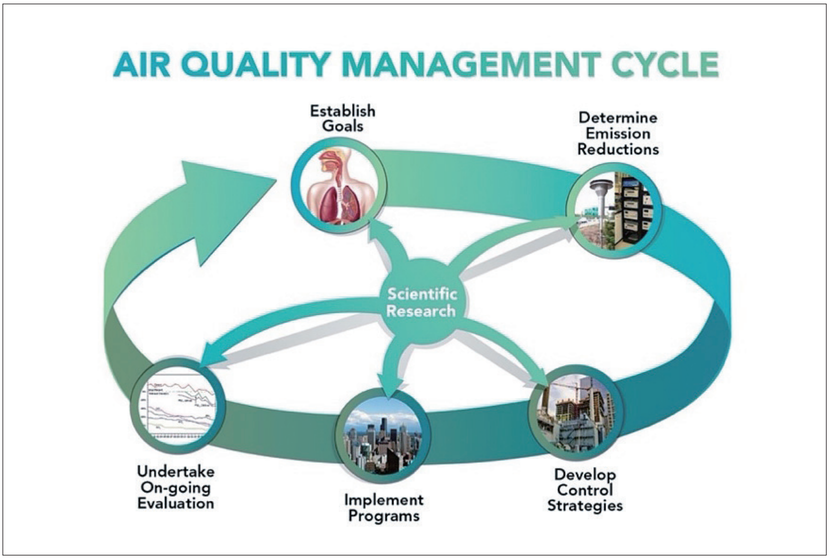
Source: KNMI/IASB/ESA/SAO

Strengths and Weaknesses of the Space-based Monitoring System. The satellite sensing has wide geographical coverage by monitoring air pollutants that travel across the boundary from local to regional to a global scale. However, it is weaker in characterizing air pollutants' composition in fine detail as compared to the ground-based monitoring systems. It is also averaged vertically, which makes it harder to distinguish the surface-level pollutant from the upper-level pollutant concentrations. On the whole, the temporal coverage of satellite sensor measurements is more limited than the ground-based monitoring devices.

5 Air Quality Management System and Process

Air Quality Management System (AQMS).

While it is important to manage major sources of pollution, controlling a single source of pollution does not prevent all air pollution. To improve the air quality at local, regional, and national levels, an integrated and holistic air quality management system (AQMS) is needed to prevent future air pollution, reduce the current level of air pollution, and minimize the adverse effect of air pollution on people and the environment. The AQMS is required in regions where air quality poses a threat to public health and ecosystem and those that show potential to be degraded by air pollution. Major constraints to the AQMS can be a lack of scientific understanding, politics, and economy. The AQMS can exist at different levels of authorities from local, regional to national level. It is composed of legislation, implementation, and assessment of control effectiveness. To successfully establish the AQMS, three categories of set standards are needed: 1) emission standards at design, construction, and operational levels; 2) emission standards of equipment and product (e.g., raw materials, fuels); and 3) ambient air quality standards. These standards are set through legislation and implemented by the respective agencies. Air quality managers and government agencies can assess whether they meet the standards.



Source: US EPA

Air Quality Management Process. The first stage of AQMS is to assess the current ambient air quality status along with emission factors from different sources. The second stage is to compare such a current status with existing standards and guidelines set by the local, regional, and national authorities. The third stage is to predict a future trend of air quality. The last stage is to come up with control strategies, implement, and revise the strategies through periodic evaluation to meet the standards set by different authorities.

6 WHO Air Quality Guidelines

Overview of WHO Air Quality Guidelines (AQG). Each country has a different threshold of air pollutants depending on its national policy and available resources. The national guidelines have become a matrix to control key air pollutants. WHO AQG is an international guideline-based on the health effects of exposure to five air pollutants, namely NO_2, O_3, SO_2 $PM_{2.5}$, and PM_{10}. It does not have any binding power, but its reasoning is based on the consensus of globally credible experts across different disciplines, which gives the highest credibility. WHO AQG can be particularly useful for setting air quality standards for countries that lack the infrastructure needed to go through their health and scientific investigations into air pollution's impact on public health. It should be noted that threshold values provided by the WHO AQG do not guarantee the complete protection of people's health against air pollution. These threshold values are a balanced value that is agreed between health experts and the feasibility of implementing policies. For many low-middle income countries, it is not feasible to achieve the AQG goals immediately. The WHO proposed the interim target values that help countries to gradually reduce air pollutants to ultimately achieve them.

Table 6.2. WHO Air Quality Guidelines

Air Pollutant	Averaging Period	AQG (g/m^3)
$PM_{2.5}$	1 year	10
	24-hour	25
PM_{10}	1 year	20
	24-hour	50
O_3	8-hour	100
NO_2	1 year	40
	1-hour	200
SO_2	24-hour	20
	10-minute	500

Source: WHO

Chapter 7

What Actions are Required?

1 Key Actions by Sectors

2 Key Actions by Stakeholders

Chapter 7

What Actions are Required?

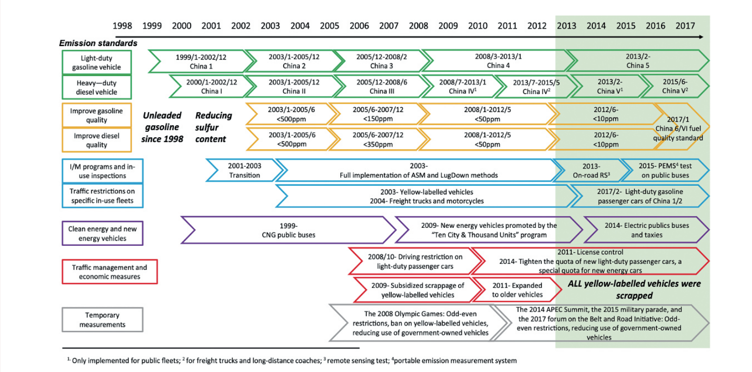
1 Key Actions by Sectors

Source: UN

Transportation Sector. The transportation sector can implement control strategies on individual vehicles or transport systems to reduce emissions. Firstly, air pollution emissions can be lowered by improving the traffic system (e.g. extra traffic signals and bus lanes). Secondly, different modes of transportation (e.g. bike and public transportation) other than passenger driving can help reduce air pollution. Thirdly, monetary policies that provide incentives for getting rid of older vehicles and increasing taxation for highly polluting fuels like diesel fuel can improve air quality. Fourthly, policies aimed towards the reduction of vehicle level emissions such as setting stringent emission standards and requiring regular inspection and maintenance by law can decrease the transport sector emission. Fifthly, technology to control individual vehicles such as requiring vehicles to install control devices can enhance the quality of air. Lastly, air pollution emission can be lessened by promoting more efficient alternative fuels like biofuels and electricity through economic incentives.

Box 7.1. Beijing Vehicle Emission Control

Beijing strengthened vehicle emission control, improved traffic management, and provided monetary incentives to cut down emissions from vehicles. Such combined efforts led to a reduction of NO_x level by 55% and $PM_{2.5}$ level by 81% during the 20 years from the transportation sector.



Source: UNEP

Residential Sector. Several measures can be taken in the residential sector to reduce air pollution. Firstly, restricting the burning of solid fuel (e.g. wood, charcoal, coal, and biomass, etc.) for households can decrease air pollution generated from the residential sector. Secondly, a transition to cleaner fuels (e.g. biogas, electricity, and liquefied petroleum gas) can improve the air quality situation in an indoor environment. This strategy can be most effective for improving indoor air quality for households that previously relied on biomass burning. Governments can aid such fuel substitution with cleaner energy through economic subsidies. Thirdly, residents can install cooking and heating stoves with high efficiency to reduce air pollution generated. Fourthly, having more windows or installing hoods can improve the circulation of air from inside to outside that can prevent air pollutants accumulating indoor. Fifthly, the kitchen can be physically separated from the rest of the households to prevent family members from being exposed to high levels of air pollution.

Box. 7.2. Twenty-Five Clean Air Measures for Asia and the Pacific

The Climate and Clean Air Coalition (CCAC), UNEP, and the Asia Pacific Clean Air Partnership in 2019 published the report called "Air Pollution in Asia and the Pacific: Science-based Solutions." It outlines the following twenty-five clean air measures for achieving safe air quality levels for 1 billion people by 2030 in the region:

1. Strengthen emission standards for road vehicles
2. Regularly maintain and inspect vehicles
3. Mainstream electric vehicles
4. Provide better mobility options
5. Control dust from construction and roads
6. Reduce emissions from international shipping
7. Improve post-combustion control
8. Strengthen industrial process emissions standards
9. Introduce efficient brick kilns technology
10. Control volatile organic compounds from oil and gas production
11. Improve solvent use and refinery controls
12. Use environmentally-friendly refrigerants
13. Provide clean cooking and heating options
14. Strictly enforce bans on household waste burning
15. Provide incentives for improved energy efficiency in households
16. Increase renewable electricity generation
17. Improve energy efficiency for industry
18. Recover coal mining gas
19. Improve livestock manure management
20. Strengthen management of nitrogen fertilizer application
21. Better management of agricultural crop residues
22. Prevent forest and peatland fires
23. Promote more efficient rice production practices
24. Stop biogas leakage from wastewater treatment
25. Improve solid waste management

Energy Sector. The major source of air pollution in the energy sector is the combustion of fossil fuel used in power generation. There are a number of ways to reduce air pollution emission from power plants. Firstly, control technologies such as departiculating, desulfurization, and denitrification can be retrofitted to existing power plants. These technologies help reduce the emission before released to the ambient air. The government's economic subsidies could aid in the installation of these control devices. Secondly, since coal-fired power plants emit more air pollutants, air pollution can be ameliorated by closing down coal-fired power plants and transitioning to cleaner sources of energy such as natural gas. Thirdly, energy from the power sector can be saved by promoting large units and retiring high-emission small units. Fourthly, an investment to renewable sources of energy (e.g. geothermal, hydroelectric, solar, and wind) can benefit the air quality in the long-run. Fifthly, setting more stringent emission standards for power generation units can help to decrease air pollution emissions.

Industrial Sector. In the industrial sector, there are various ways in which air quality can be improved. Firstly, the industry sector can first and foremost increase energy efficiency. This is especially important for industries that use intensive levels of energy like oil refining and chemical industries. Secondly, the government can set regulations and provide subsidies for high-pollution industries to either close down or implement the end-of-pipe technology, which can help reduce the level of emission from those industries. Thirdly, mandating industrial sectors to implement such end-of-pipe technology (i.e. scrubbers) through regulation is another way of improving air quality. Fourthly, having a stringent air pollutant emission level for industries can lower the amount of air pollution being emitted into the atmosphere.

Agricultural Sector. There are multiple actions that the agricultural sector can take to reduce air pollution. First of all, the government can prohibit the open burning of agricultural residues. Secondly, the reduction in ammonia emission, which is essential for the agricultural sector, can be achieved by controlling mineral fertilizer. Many mineral fertilizers contain significant amounts of nitrogen and urea which is particularly known to convert immediately into ammonia. One way of controlling it is by using urease inhibitors. Thirdly, ammonia emissions can also be reduced by using ammonium nitrate fertilizer instead of urea fertilizer. Fourthly, livestock farming entails a great amount of manure (i.e. animal dung), which is a significant source of air pollution. Better management methods for manure can improve air quality. The quickest measure is to dispose of the manure beneath the surface and prevent manure from being directly exposed to the atmosphere. A more technologically advanced method is incorporating manure directly into slurry. Fifthly, the deeper injection of manure underneath the surface can bring about better air quality.

2 Key Actions by Stakeholders

Citizens. There are several day-to-day life choices that people can make to help improve air quality. First of all, it is important to conserve energy at home, work, and in vehicles. People can refrain from excessive heating or cooling and set to a moderate temperature. Secondly, people can use alternatives to driving such as using public transportation like buses and subways, riding bikes or walking, or doing a carpool if other modes of transportation are not available. Thirdly, using eco-friendly products (i.e. paints, cleaning products, personal care products) can help reduce the release of VOCs to the atmosphere. Fourthly, if one possesses a car, boat, or other devices with engines, keeping regular inspection to check the status of the car and maintenance can help implement necessary control devices that help reduce vehicle emission. Fifthly, people can refrain from burning biomass at home, including burning wood at a fireplace and burning waste or leaves in the backyard. Sixthly, they can buy energy-efficient equipment and products for buildings and households. Seventhly, asking or petitioning local officials for data on local air quality, as well as controlling highly polluting facilities, can bring about changes. Eighthly, it is an efficient way to organize trash clean-up and tree planning activities as a community and refrain from overly consuming products. Finally, fueling the vehicle at times of lower temperature (i.e. evening instead of noon) can be helpful.

Box 7.3. Public Opinion Matters

- Increasing access to air pollution information through mobile phone applications for air pollution information
- Increasing voices of citizens for calling actions

Source: UN Photo/J Bleibtreu

Government. The role of the government is crucial for controlling air pollution as it sets the national ambient air quality standards and various economical subsidies program. There are actions that the government can take to improve the air quality from a local, regional to a national scale. The most important step to consider is incorporating the WHO Air Quality Guideline into the policymaking process, for example, by strengthening the national ambient air quality standards and management system to fully protect the public's health from air pollution. Updating the policy with the newest findings is also vital. The second way is to set up a detailed emission inventory of key targeted pollutants for each sector and implement a well-organized monitoring system to track the emission. These measures can help identify the major sources of emission and be controlled if necessary. Thirdly, the government can implement comprehensive air quality monitoring and measuring systems at local, regional, and national levels. This system data can be used to inform the public, annual air quality assessment report, and health assessment studies to protect people from the adverse effects of air pollution. Fourthly, the government can develop control strategies at different geographical scales from local, regional to a national scale, and strengthen cooperation among these three scales to best to tackle the air pollution problem. The promotion of cooperation with neighboring countries and across the globe is also an essential step to mitigate the transboundary impacts of air pollution. Moreover, the government can invest more money in renewable energy that emits less air pollutants. Lastly, interdisciplinary research and education opportunities should be promoted by the government.

Box 7.4. China's Plan to Reduce Air Pollution

China launched a bold plan to reduce air pollution in 2013 and reduced PM2.5 and SO2 by 42% and 68% respectively in 74 major cities by 2018. An evaluation report by the Chinese Ministry of Ecology and Environment summarized the impacts of policy measures on air pollution as follows:

1. Rule of Law: Improvement of legal framework, combining administrative and judicial efforts, and strengthened law enforcement
2. Science and Technology Support: Revising air quality standards, improving air quality monitoring network, improving pollution source inventory and analysis, and identifying causes of severe air pollution and solutions in each city
3. Comprehensive Emission Cuts: Upgrading industrial standards and companies, industrial restructuring, optimizing energy structure, pollution control of "fuel, road, vehicle," and treatment of non-point source pollution
4. Management Innovation: Management system reform, innovative enforcement methods, carrying through responsibilities by provincial, city and country governments, response to severe pollution by forecasting and emergency response, improved economic policies, and open environmental information
5. Social Participation: Easier information access, public interest litigation, public awareness, reporting environmental complaints, and engaging in decision making

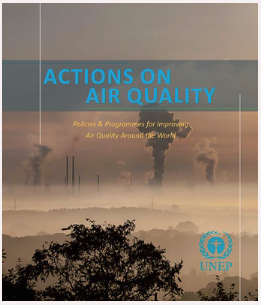
Source: China Air Quality Improvement Report: 2013-2018, Ministry of Ecology and Environment, China, 2019

Box 7.5. The Republic of Korea's Comprehensive Management Plan on PM

The Republic of Korea aims to reach $PM_{2.5}$ concentration to 16g/m^3 by 2024, which is a 35% reduction of $PM_{2.5}$ concentration as compared to that of 2016 (26g/m^3) through the following 15 major actions:

1. Implement Total Air Pollution Load Management System nationwide
2. Reinforce inspection and control on emission by industrial enterprises
3. Encourage scrappage of old diesel vehicles and expand the supply of low-emission vehicles
4. Reinforce the management standards for ships and ports
5. Reinforce the management of old construction equipment
6. Reduce PM emission from coal-based power stations
7. Transition to cleaner energy for power stations
8. Reinforce the management of emission from livestock waste
9. Expand the supply of low-NO_x boiler
10. Implement a reinforced PM reduction management system during high PM episodes
11. Improve the management of indoor air quality
12. Promote East-Asia cooperation on PM reduction
13. Promote and expand the practical cooperation mechanism
14. Support the businesses to develop PM reduction technology
15. Meet the social agreement through active participation of citizens

Box 7.6. Actions on Air Quality: Policies and Programmes for Improving Air Quality around the World



This publication offers an overview of the progress being made to choose and perform major actions that can substantially improve air quality.

Read in full:
http://wedocs.unep.org/handle/20.500.11822/7677

Chapter 8

What are Regional and Global Cooperation Mechanisms?

1 Regional Cooperation Mechanisms

2 Global Cooperation Mechanisms

Chapter 8

What are Regional and Global Cooperation Mechanisms?

1 Regional Cooperation Mechanisms

Regional cooperation of air pollution is important as air pollutants are transported across the borders and affect the air quality of neighboring countries. The nature of these air pollutants increases the need for a collective measure to control air pollution. Regional cooperation mechanisms generally entail the promotion of sharing and standardization of monitoring data, provision of collective measures to control targeted air pollutants, smooth exchange of data, stronger scientific cooperation among experts in different countries, as well as the preparation for collective health and environmental assessment reports. Some examples of regional cooperation mechanisms include the Convention on Long-range Transboundary Air Pollution, ASEAN Agreement on Transboundary Haze Pollution, Acid Deposition Network in East Asia, and the North-East Asia Clean Air Partnership.

The **Convention on Long-range Transboundary Air Pollution (CLRTAP)** was signed in 1979 as the first international treaty to deal with air pollution on a broad regional basis. Since then, the Parties to the Convention adopted eight protocols to guide the reduction of air pollutants including sulfur oxides, nitrogen oxides, volatile organic compounds, heavy metals, persistent organic pollutants, ground-level ozone and particulate matter. The Parties include 51 countries, namely the member States of UNECE.

Box 8.1. Eight Protocols of the CLRTAP Convention

The 1999 Gothenburg Protocol to Abate Acidification, Eutrophication, and Ground-level Ozone:

- Set up a national emission limitation from 2010 to 2020 for SO_2, NO_X, VOC, and NH_3
- Mandated the Parties to report annual emission inventory and provide emission projection
- Amended the following in 2012:
  - Extended the reduction commitment beyond 2020
  - Made an agreement to include PM (including BC) emission reduction
  - Created mandatory emission values for different activities (Annexes VI and XI)
  - Established solvent management plans for activities (Annex VI)
  - Introduced flexibility to include new Parties (e.g. Eastern and South-East Europe, the Caucasus and Central Asia)

The 1998 Aarhus Protocol on Persistent Organic Pollutants (POPs):

- Focused on 16 substances (e.g. 11 pesticides, 2 industrial chemicals, and 3 contaminants)
- Aimed to get rid of discharges and emissions of those 16 substances
- Amended in 2009: Introduced 7 new substances, and made changes to annexes

The 1998 Aarhus Protocol on Heavy Metals:

- Targeted three heavy metals of cadmium, lead and mercury
- Amended in 2012: Introduced flexibility to add new countries and added more stringency in controlling heavy metal emissions

The 1994 Oslo Protocol on Further Reduction of Sulphur Emissions:

- Set sulphur emission limitations until 2010 and beyond

The 1991 Geneva Protocol concerning the Control of Emissions of Volatile Organic Compounds or their Transboundary Fluxes:

- Aimed to reduce VOCs with three options to meet the emission reduction target
- Amended in 1996: Advised on control technology (Annex III) from off-road transportation means

The 1988 Sofia Protocol concerning the Control of Emissions of Nitrogen Oxides or their Transboundary Fluxes:

- Aimed to reduce NO_X emission
- Amended in 1996: Amended the technical annex on control technologies to off-road transportation means

The 1985 Helsinki Protocol on the Reduction of Sulphur Emissions or their Transboundary Fluxes by at least 30%:

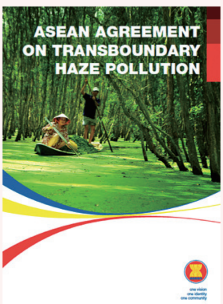
- Reduced sulphur emission by 30%
- Further addressed in 1994 and 1999 protocols

The 1984 Geneva Protocol on Long-term Financing of the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP):

- Served as an instrument for international cost-sharing of monitoring programme composed of three components

The **ASEAN Agreement on Transboundary Haze Pollution (AATHP)** was adopted in 2002 to reduce haze pollution, which is mainly caused by land clearing for agricultural uses in South-East Asia. The Agreement facilitates development and implementation of measures, system monitoring, assessing, and warning, promotion of knowledge and technology exchange, response to member States affected by transboundary haze pollution, as well as the adoption of legal, administrative and other relevant measures. Its members include 10 ASEAN member States and the ASEAN Secretariat serves as the interim Coordinating Centre for Transboundary Haze Pollution Control (ACC). The Agreement is also supported by the ASEAN Task Force on Peatlands and ASEAN Haze Fund.

Box 8.2. ASEAN Agreement on Transboundary Haze Pollution



Read in full:
http://haze.asean.org/2019/08/asean-agreement-on- transboundary-haze-pollution-reprint-2019/

The **Acid Deposition Monitoring Network in East Asia (EANET)** was established in 2001 as an intergovernmental initiative to create a common understanding of the state of acid deposition problems caused by sulfuric and nitric acids. Key activities include acid deposition monitoring, compilation, evaluation, storage and provision of data, promotion of quality assurance and quality control (QA/QC) activities, implementation of technical support and capacity building activities, and the promotion of research and studies related to acid deposition problems. Its members include 13 countries in South-East Asia and North-East Asia. The Secretariat is hosted by UNEP Asia and the Pacific Office.

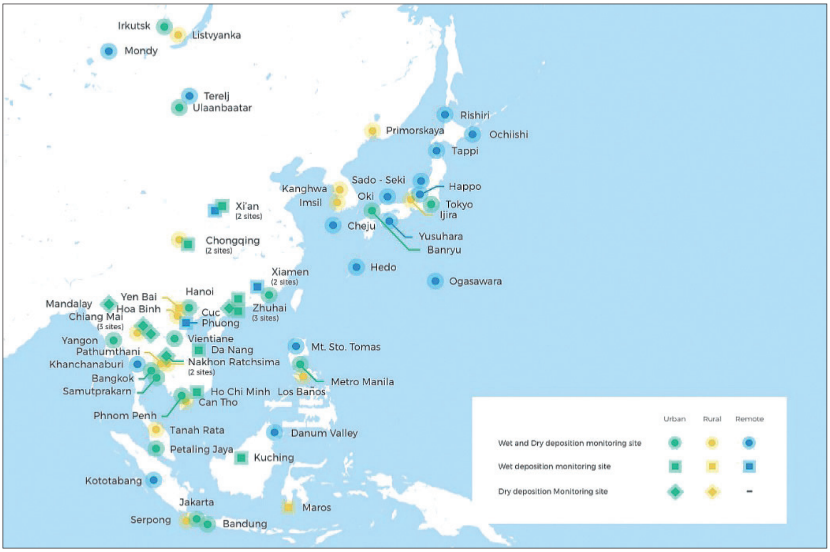


Figure 8.1. EANET Monitoring Sites (Source: EANET)

The **North-East Asia Clean Air Partnership (NEACAP)** was launched in 2018 by member States of the North-East Asian Subregional Programme for Environmental Cooperation (NEASPEC), which had carried out technical projects on transboundary air pollution since mid-1990s, to promote cooperation on science, policy, and technical aspects of air pollution, and enhance information and experience exchange. Key activities include exchanging relevant emission information and data of target pollutants including particulate matter and ozone and their precursors, coordinating with relevant mechanisms and synthesize their results, and proposing potential technical and policy measures to tackle air pollution. Members include six North-East Asian countries. The Secretariat is hosted by UNESCAP East and North-East Asia Office.

2 Global Cooperation Mechanisms

In recent years, extending from regional cooperation, there is an increasing call for collective inter-regional and global actions from various international forums. The UN Environment Assembly Resolution 3/8 adopted in 2017 addressed the member States to strengthen cooperation across governments and with UNEP to respond to air pollution globally. WHO held the first Global Conference on Air Pollution and Health from October 30 to November 30, 2018, to discuss how to save lives through global actions that lead to the improvement of air quality and climate change.

First WHO Global Conference on Air Pollution (2018) (Source: WHO)

Based on 40 years' experience in facilitating regional cooperation, CLRTAP also expands its global outreach. The 38th session of the CLRTAP Executive Body in December 2018 held a special session, "Global Event on Clear Air" to promote global cooperation towards clean air. Non-members of UNECE, namely Argentina, Brazil, Ghana, India, Mexico, Mongolia, Pakistan, and the Republic of Korea, attended this global event.

Following this Global Event, the 39th session in 2019 decided to establish a forum for international cooperation on air pollution. The objective of this forum is to involve both ECE and non-ECE countries, as well as organizations to facilitate international exchange of information and mutual learning on both the scientific/technical and policy levels.

Chapter 9

Resources

1 Policy-related Reports

2 Health-related Reports

3 Climate-related Reports

4 Useful Websites

Chapter 9

Resources

1 Policy-related Reports

- Mongolia Voluntary National Review Report 2019. Government of Mongolia. https://sustainabledevelopment.un.org/content/documents/23342MONGOLIA_VOLUNTARY_NATIONAL_REVIEW_REPORT_2019.pdf

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2 Health-related Reports

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3 Climate-related Reports

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2021. 1

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National Council on Climate and Air Quality of the Republic of Korea