AIR POLLUTION IN ASIA AND THE PACIFIC:
SCIENCE-BASED SOLUTIONS

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Environment Programme

Asia Pacific Clean Air Partnership

CLIMATE &
CLEAN AIR
COALITION
TO REDUCE SHORT-LIVED
CLIMATE POLLUTANTS

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ASIA PACIFIC CLEAN AIR PARTNERSHIP

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FOREWORD

It is an unfortunate fact that breathing clean air, the most basic human need, has become a luxury in many parts of the world. And while we have beaten many of the big killers of the past, air pollution is now ranked as one of the most serious health threats on the planet, with around a third of global air pollution deaths occurring in Asia and the Pacific. The good news, however, is that the region is also home to numerous and tested solutions that can help beat pollution, save lives and protect our planet.

Air Pollution in Asia and the Pacific: Science-based Solutions identifies 25 clean air measures that can positively impact human health, crop yields, climate change and socio-economic development, as well as contribute to achieving the Sustainable Development Goals. Implementing these measures could help 1 billion people breathe cleaner air by 2030 and reduce global warming by a third of a degree Celsius by 2050.

The top 25 measures not only represent wins for cities and countries looking to improve air quality, but also provide next-generation business opportunities and boost economic growth. India's east-coast state of Maharashtra and its capital city of Mumbai, for example, are embracing electric mobility, aiming to increase the number of electric vehicles in the state to 500,000, creating thousands of jobs and positioning the state as a globally competitive manufacturing destination for electric vehicles and their components.

We have seen how cooperation can lead to positive impacts. In China, the city of Shenzhen, with support from the national government and local transport agencies, is the first to adopt a fully electric solution for its public network of more than 16,000 buses. In Nepal, brick kilns destroyed during the 2015 earthquake have been rebuilt to be safer, less polluting and more efficient through collaboration between kiln owners and technical experts. In Toyama, Japan, integrating transport planning and waste management while promoting renewable energy and energy saving has made the air cleaner and the city more climate resilient.

This report underlines the importance of strong engagement with governments, the private sector and civil society – and the importance of simple and clear communication with citizens to be able to fully-implement recommended solutions.

I hope the report will inspire strong action from the Asia and Pacific region in our efforts to beat air pollution.

JOYCE MSUYA
Acting Executive Director
United Nations Environment Programme
December 2018

MESSAGE FROM CO-CHAIRS

Air Pollution in Asia and the Pacific: Science-based Solutions **aims to support efforts to reduce air pollution in Asia and the Pacific by proposing cost-effective options suited to the countries of the region.**

Air quality in Asia and the Pacific – what is its status?

The impact of air pollution on human health constitutes a serious public health crisis across Asia and the Pacific. About 4 billion people, around 92 per cent of the region's population, are exposed to levels of air pollution that pose a significant risk to their health: exposure to pollution levels in excess of the World Health Organization (WHO) Guideline for public health protection is associated with elevated risks of premature death and a wide range of illnesses. Reducing this health burden requires further action in Asia and the Pacific to reduce emissions that lead to the formation of fine particulate matter ($PM_{2.5}$) and ground-level ozone, which undermine people's health and well-being as well as food production and the environment.

Fortunately, governments in Asia and the Pacific have already adopted and implemented policies to reduce pollution levels. Without these, population-weighted exposure to harmful $PM_{2.5}$ would be expected to grow by more than 50 per cent by 2030, based on the region's projected economic growth of 80 per cent over the same period. These policies deliver significant benefits for air quality and health, a considerable achievement. However, they are not enough. Further action is necessary if the people of Asia and the Pacific are to enjoy air quality that conforms to the WHO Guideline.

Air quality in Asia and the Pacific – what can be done?

Air Pollution in Asia and the Pacific: Science-based Solutions uses the highest quality data available and state-of-the-art modelling to identify the most effective 25 measures to reduce air pollution. The analysis, which takes the region's considerable diversity into account, groups the selected measures into three categories that are fully described within the report:

i. conventional emission controls focusing on emissions that lead to the formation of fine particulate matter;

ii. further (next-stage) air-quality measures for reducing emissions that lead to the formation of $PM_{2.5}$ and are not yet major components of clean air policies in many parts of the region; and

iii. measures contributing to development priority goals with benefits for air quality.

If the 25 identified measures are effectively implemented, 1 billion people in Asia could enjoy air quality that conforms to the WHO Guideline by 2030, compared to only about 360 million in 2015. The reductions in outdoor air pollution could reduce premature mortality by a third, and about 2 million premature deaths from indoor air pollution could be avoided each year.

These 25 measures would also provide benefits for food and water security, environmental protection and the mitigation of climate change.

MESSAGE FROM CO-CHAIRS

Air Quality in Asia and the Pacific – how to achieve benefits?

Regional and national differences in priorities for action and ease of implementation require a flexible approach to tackling air pollution, so this report provides a range of options for countries to consider in the context of their national circumstances.

The region already has considerable experience with the implementation of measures to reduce pollutant emissions, but there is a need to strengthen compliance with existing policies and improve their alignment in order to enhance both their implementation and their effectiveness.

Improving compliance will require significantly greater institutional and human resource capacity to manage pollution-related issues in a wide range of agencies. This report discusses how better alignment of policies will require carefully designed inter-agency coordination mechanisms.

The focus of most air pollution prevention policies is on cities. However, as this report identifies, regions around cities contribute significantly to poor air quality within cities due to the atmospheric transport of air pollutants. To manage urban air quality effectively, regional, national, urban and rural authorities with responsibility for activities resulting in emissions need to collaborate more closely. As $PM_{2.5}$ and ground-level ozone are regional air pollutants, joint regional efforts and institutional mechanisms are also required to address them.

Many challenges arise from the findings of ***Air Pollution in Asia and the Pacific: Science-based Solutions.*** For example, the successful implementation of some smaller-scale measures may require forms of governance that facilitate coordination within and across stakeholder organizations at various levels of decision making. Collaborative regional and international initiatives also have an important role to play, as they can help provide the financial, technological and capacity-building support needed to carry through many of the proposed measures.

Despite these challenges, the benefits of implementing these 25 cost-effective measures to reduce air pollution outweigh the expense many times over, and we hope that this report will contribute to effective action.

The Co-Chairs of *Air Pollution in Asia and the Pacific: Science-based Solutions*

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KEY MESSAGES

KEY MESSAGES

THE NEED

Only the few ...

Less than 8 per cent of the population of Asia and the Pacific enjoyed healthy air – within the World Health Organization (WHO) Guideline – in 2015. That means that around 4 billion people, the other 92 per cent of the population, spread unevenly across the region and with the highest numbers living in South and East Asia, are exposed to levels of air pollution that pose significant risks to their health. Improving the lives of such a vast number of people requires action to reduce the emissions that result in the formation of fine particulate matter ($PM_{2.5}$) and ground-level ozone, both of which damage human health and well-being, as well as food production and the environment.

It may not get worse, but will it get better?

If current policies aimed at limiting emissions are effectively introduced and enforced, air quality will be no worse in 2030 than it was in 2015, despite population growth, rapid urbanization and an ever-increasing demand for goods and services. But nor will it be any better. This suggests that current policies are mitigating air pollution in valuable but limited ways. The 80 per cent economic growth forecast by 2030 compared with 2015 could be achieved with no further increase in air pollution while lifting tens of millions of people out of poverty. However, this still leaves more than 4 billion exposed to health-damaging levels of air pollution. Further action is needed to move towards the WHO Guideline and protect public health.

THE SOLUTIONS

The widespread effective implementation of only 25 measures will dramatically improve the situation

State-of-the-art modelling has been conducted on several hundred potential ways to reduce air pollution. The most effective 25 measures were selected as the best proven options, benefiting human health and the environment with regard to food security, air, water and soil quality, biodiversity and climate, whilst helping achieve the Sustainable Development Goals (SDGs).

THE BENEFITS

Improving health

By implementing the top 25 clean air measures, 22 per cent of the region's population, around 1 billion people, could enjoy air quality within the WHO Guideline by 2030, compared to less than 8 per cent in 2015. The number of people exposed to pollution above the highest WHO Interim Target could fall by 80 per cent to 430 million. Furthermore, premature mortality from outdoor air pollution could decline by about a third, and an additional 2 million premature deaths a year from indoor air pollution could be avoided.

Improving food security and protecting the environment

Ground-level ozone is the most important air pollutant responsible for reducing crop yields, and thus affects food supply. Implementing the top 25 clean air measures could reduce estimated ozone-induced crop losses considerably – by 45 per cent for maize, rice, soy and wheat combined. And, as ground-level ozone affects productive grasslands and forests in similar ways, adoption of the package of measures would also benefit the health of natural ecosystems. The measures will also reduce nitrogen and sulphur deposition to ecosystems and have benefits for water and soil quality, as well as biodiversity.

Enhancing water security

Additional warming due to black carbon and dust in the atmosphere and their deposition on glaciers and snowfields in the Hindu Kush-Karakorum-

Himalayan-Tibetan area is strongly linked to accelerated melting of glaciers and snowfields in the region. A reduction in particulate emissions from implementing the top 25 clean air measures will slow the melting of glaciers and snowfields, reduce the risk of disasters related to glacier lake outburst floods, and help mitigate water insecurity for billions of people.

Mitigating climate change

Implementing the top 25 clean air measures will benefit efforts to mitigate climate change. It could reduce carbon dioxide emissions in 2030 by almost 20 per cent relative to baseline projections and potentially decrease the expected warming by a third of a degree Celsius by 2050. This would be a significant contribution to the Paris Agreement target of keeping global temperature rise this century well below 2°C.

Contributing to the Sustainable Development Goals

The top 25 clean air measures will aid countries in their efforts to achieve the SDGs. Implementing them will improve air quality and mitigate climate change, directly contributing to the realization of SDG 3: Good Health and Well-being, SDG 11: Sustainable Cities and Communities, SDG 12: Responsible Consumption and Production and SDG 13: Climate Action. Measures applied individually or in groups will also contribute directly or indirectly to the achievement of all the other 13 SDGs and their linked targets.

MAKING IT HAPPEN

Providing options for Asia and the Pacific

The top 25 clean air measures are not equally appropriate across the whole region. While the measures are a package, the diversity of sub-regions and countries in the region will mean tailoring the prioritization and implementation of the measures to national realities.

Requiring a small share of the region's future growth

Implementation of the top 25 clean air measures across the region is projected to cost US$ 300–600 billion per year, only about one twentieth of the increase of US$ 12 trillion in annual gross domestic product (GDP) that is projected by 2030. In addition to delivering substantial benefits to human health, food production, environmental protection and climate change mitigation, a basket of co-benefits will accrue, including savings on pollution control.

Financing the clean air measures

Several of the top 25 clean air measures are aligned with national development priorities and could be supported from domestic public finance. The private sector and businesses are ready to invest in cleaner technologies, provided a favourable enabling environment is in place. Concessional or low-interest loans can support governments and other stakeholders in implementing the measures, while climate finance mechanisms are available for measures that reduce air pollution and mitigate greenhouse gas emissions. Multilateral and bilateral funding institutions could align their air pollution strategies to the top 25 clean air measures, with research institutes and networks helping build the additional technical capacity needed to introduce and effectively implement the measures.

Mobilizing partnerships for multiple benefits

Continued economic growth will remain critical, but economic growth alone will not be enough to lead to the successful adoption and effective implementation of the top 25 clean air measures. That will require concerted efforts and integrated action from governments, businesses and civil society. The introduction and successful implementation of the measures will entail building bridges between traditional decision-making structures and breaking down barriers to effective partnership. The careful choice and implementation of the 25 clean air measures could foster cooperation between a variety of ministries, local authorities, industries and civil society organizations. Multiple partners working together can implement change for the greater good and sustainable development of Asia and the Pacific.

TABLE A: THE TOP 25 CLEAN AIR MEASURES

Regional application of conventional measures

Post-combustion controls	Introduce state-of-the-art end-of-pipe measures to reduce sulphur dioxide, nitrogen oxides and particulate emissions at power stations and in large-scale industry
Industrial process emissions standards	Introduce advanced emissions standards in industries, e.g., iron and steel plants, cement factories, glass production, chemical industry, etc.
Emissions standards for road vehicles	Strengthen all emissions standards; special focus on regulation of light- and heavy-duty diesel vehicles
Vehicle inspection and maintenance	Enforce mandatory checks and repairs for vehicles
Dust control	Suppress construction and road dust; increase green areas

Next-stage air quality measures that are not yet major components of clean air policies in many parts of Asia and the Pacific

Agricultural crop residues	Manage agricultural residues, including strict enforcement of bans on open burning
Residential waste burning	Strictly enforce bans on open burning of household waste
Prevention of forest and peatland fires	Prevent forest and peatland fires through improved forest, land and water management and fire prevention strategies
Livestock manure management	Introduce covered storage and efficient application of manures; encourage anaerobic digestion
Nitrogen fertilizer application	Establish efficient application; for urea also use urease inhibitors and/or substitute with, for example, ammonium nitrate
Brick kilns	Improve efficiency and introduce emissions standards
International shipping	Require low-sulphur fuels and control of particulate emissions
Solvent use and refineries	Introduce low-solvent paints for industrial and do-it-yourself applications; leak detection; incineration and recovery

TABLE A: THE TOP 25 CLEAN AIR MEASURES (contd.)

Measures contributing to development priority goals with benefits for air quality	
Clean cooking and heating	Use clean fuels – electricity, natural gas, liquefied petroleum gas (LPG) in cities, and LPG and advanced biomass cooking and heating stoves in rural areas; substitution of coal by briquettes
Renewables for power generation	Use incentives to foster extended use of wind, solar and hydro power for electricity generation and phase out the least efficient plants
Energy efficiency for households	Use incentives to improve the energy efficiency of household appliances, buildings, lighting, heating and cooling; encourage rooftop solar installations
Energy efficiency standards for industry	Introduce ambitious energy efficiency standards for industry
Electric vehicles	Promote the use of electric vehicles
Improved public transport	Encourage a shift from private passenger vehicles to public transport
Solid waste management	Encourage centralized waste collection with source separation and treatment, including gas utilization
Rice paddies	Encourage intermittent aeration of continuously flooded paddies
Wastewater treatment	Introduce well-managed two-stage treatment with biogas recovery
Coal mining	Encourage pre-mining recovery of coal mine gas
Oil and gas production	Encourage recovery of associated petroleum gas; stop routine flaring; improve leakage control
Hydrofluorocarbon (HFC) refrigerant replacement	Ensure full compliance with the Kigali Amendment


SPEAKERS

INTRODUCTION

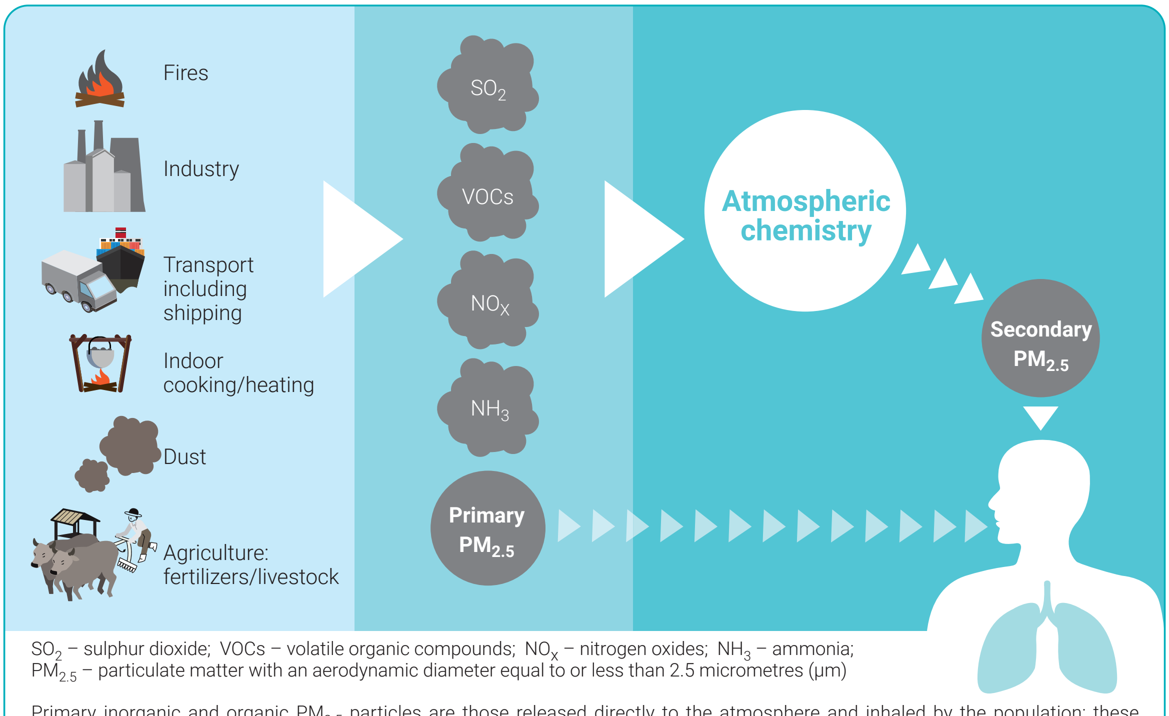
INTRODUCTION

AIR POLLUTION IMPACTS ON HUMAN HEALTH

The impact of air pollution on human heath represents a serious public health crisis across Asia and the Pacific. Fewer than 8 per cent of the region's people are exposed to levels of air pollution that do not pose a significant risk to their health according to the World Health Organization (WHO) Guideline. There is now sufficient evidence from epidemiological studies in Asia and the Pacific that exposures to $PM_{2.5}$ and ground-level ozone are the most health damaging and account for large attributable health burdens.

Fine particulate matter

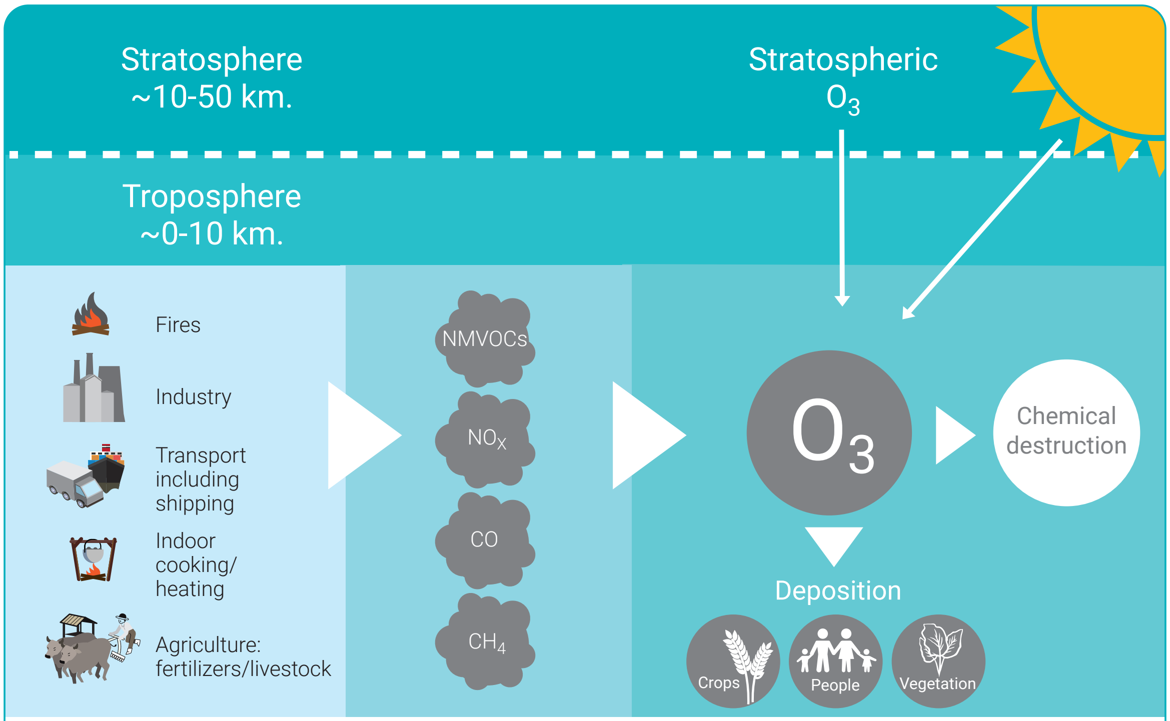
Fine particles are directly emitted during the combustion of fossil fuels and biomass including forest and peat fires, and from industrial processes; these particles include fly ash, various metals, salts, and carbonaceous species including black and organic carbon (Figure 1). Particle emissions also originate from natural sources such as soil dust and sea salt. Another substantial fraction of fine particles is formed in the atmosphere through chemical reactions involving gaseous emissions. Sulphur dioxide, nitrogen oxides and volatile organic compounds from fuel combustion and industrial processes, and ammonia from agricultural activities are the main contributors to the formation of fine particulates in this way. In this report, fine particulate matter is considered to be $PM_{2.5}$ – particles with an aerodynamic diameter equal to or less than 2.5 micrometres (µm). There is a variable relationship with PM_{10}, particles with an aerodynamic diameter equal to or less than 10 µm, that may depend on the sources as well as the physics and chemistry of the atmosphere.The relationship may vary with location, season and weather conditions.



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 $PM_{2.5}$



NMVOCs – Non-methane volatile organic compounds; NO_X – nitrogen oxides; CO – carbon monoxide; CH_4 – methane; O_3 – ozone

FIGURE 2: SOURCES OF GROUND-LEVEL OZONE

Ground-level ozone

Ground-level ozone causes serious damage to human health and vegetation. It is formed in the atmosphere by reactions between carbon monoxide, nitrogen oxides, and volatile organic compounds, including methane, in the presence of sunlight (Figure 2). The substances that contribute to the formation of ozone are emitted from a wide range of sources including vehicles, industrial production, fuel combustion, natural emissions from vegetation and soils, vegetation fires including wildfires, controlled burns and agricultural burning, and solvents, as well as emissions from waste disposal. Nitrogen oxides reduce ozone close to their emission sources, usually within urban areas, but enhance its formation downwind. Emissions of volatile organic compounds are potent contributors to ozone formation at the urban scale, and ozone has a lifetime in the atmosphere of the order of several weeks, sufficiently long for it to be transported over longer distances.

World Health Organization guidelines

The WHO has established air quality guidelines to protect human health, with a value for $PM_{2.5}$ of 10 micrograms per cubic metre (μg/m³) as an annual mean concentration in ambient air (Table 1).

TABLE 1: WORLD HEALTH ORGANIZATION AIR QUALITY CRITERIA FOR $PM_{2.5}$

Annual mean $PM_{2.5}$ concentration		**WHO Air Quality Criteria**
35 μg/m³	●	WHO Interim Target 1
25 μg/m³	●	WHO Interim Target 2
15 μg/m³	●	WHO Interim Target 3
10 μg/m³	●	WHO Guideline

While based on scientific evidence of health impacts, this level may seem aspirational, and even out of practical reach for some countries given their current positions. As a result, the WHO has established Interim Targets as milestones along the way towards an end-goal of achieving the WHO Guideline value.

Looking forward

Fortunately, governments in the Asia and Pacific region have successfully adopted and implemented policies that have reduced pollution levels and will continue to do so in future. Without them, population-weighted exposure to harmful particulate matter would have been expected to grow by more than 50 per cent by 2030, based on the region's projected 80 per cent economic growth. Although current policies deliver clear and significant improvements in air quality and provide health benefits, a considerable achievement, further action is needed to achieve the WHO Guideline and protect public health.

Air Pollution in Asia and the Pacific: Science-based Solutions

Air Pollution in Asia and the Pacific: Science-based Solutions, the first comprehensive, solution-oriented, interdisciplinary scientific assessment of the air pollution outlook and policy measures in Asia and the Pacific, and this summary, have been prepared in response to Resolution 1/7 of the First Session of the United Nations Environment Assembly in 2014, which called for UNEP to prepare regional reports on air quality issues.

This report is the product of close collaboration between the Asia Pacific Clean Air Partnership (APCAP) and the Climate and Clean Air Coalition (CCAC). The assessment process was chaired by three Co-Chairs from the Asia and Pacific region: Professor Jiming Hao, Tsinghua University, China; Professor Yun-Chul Hong, Seoul National University, Republic of Korea; and Professor Frank Murray, Murdoch University, Australia, and was coordinated by: APCAP; CCAC Secretariat; Institute for Global Environmental Strategies (IGES); Stockholm Environment Institute (SEI); UN Environment, Asia and the Pacific Office; and International Institute for Applied Systems Analysis (IIASA).

Aims

The report and its summary aim to support efforts to address air pollution in Asia and the Pacific by providing options for tackling air pollution in the context of the SDGs. To this end, it brings together evidence of historical trends with future development perspectives and provides detailed analyses of past and future economic trends and their implications for ambient and indoor air pollution.

From there, the report identifies a detailed portfolio of 25 cost-effective measures for technological and policy interventions that would contribute to the achievement of the SDGs while delivering the greatest benefits for human health, crop yields, climate and the environment, as well as socio-economic development.

The report provides a clear picture of the benefits to be gained by adopting the measures and offers some implementation guidance through real-life case studies. It is also hoped that the report will act as a platform to share experiences with practical actions to prevent and control atmospheric pollution across the Asia and Pacific region.

Structure

Chapter 1 assesses from a regional perspective the many impacts that poor air quality can have, not only on human health, but on the environment, climate and development priorities.

Chapter 2 identifies the priority measures that most effectively reduce health impacts across the region and help to meet other development goals. This includes the benefits of taking action on air pollution for mitigating climate change.

Chapter 3 explains how these measures can be implemented and provides examples of where they have been successfully applied in the region. It also identifies enabling environments and factors supporting their implementation at scale across the region.

Target audience

The main report, ***Air Pollution in Asia and the Pacific: Science-based Solutions,*** is intended to be used by professionals and practitioners to inform policy and decision makers working in the areas of air pollution and climate change to develop national policies and strategies to address air pollution using proven, cost-effective, readily implementable measures.

Asia and the Pacific

In the report, results are presented as aggregates for four Asia and the Pacific sub-regions (Figure 3). While based on the sub-region components practically defined by the UN Environment Asia and the Pacific Office and the World Bank, countries were re-grouped for the purposes of modelling to take account of the availability of data and ensure the scientific consistency of the modelling results. These sub-regions are used for scientific convenience and have no official or administrative significance. The modelling studies were conducted using available data on emissions and ambient concentrations of the relevant pollutants in Asia, but such data were obtainable for only a few countries in the Pacific area. The absence of data of a suitable quality for large parts of the Pacific prevented modelling to the necessary level of reliability in the Pacific.

As a result, the sub-regions used in the report are composed as follows:

- **East Asia** (modelled East Asia) includes China, Democratic People's Republic of Korea and Mongolia (and excludes Japan and Republic of Korea);
- **Southeast Asia** (modelled Southeast Asia) includes Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Thailand and Viet Nam (and excludes Brunei Darussalam and Singapore);
- **South Asia** (modelled South Asia) includes Afghanistan, Bangladesh, Bhutan, India, Iran, Maldives, Nepal, Pakistan and Sri Lanka; and
- **High-income countries** (modelled high-income countries) includes Brunei Darussalam, Japan, Republic of Korea and Singapore.

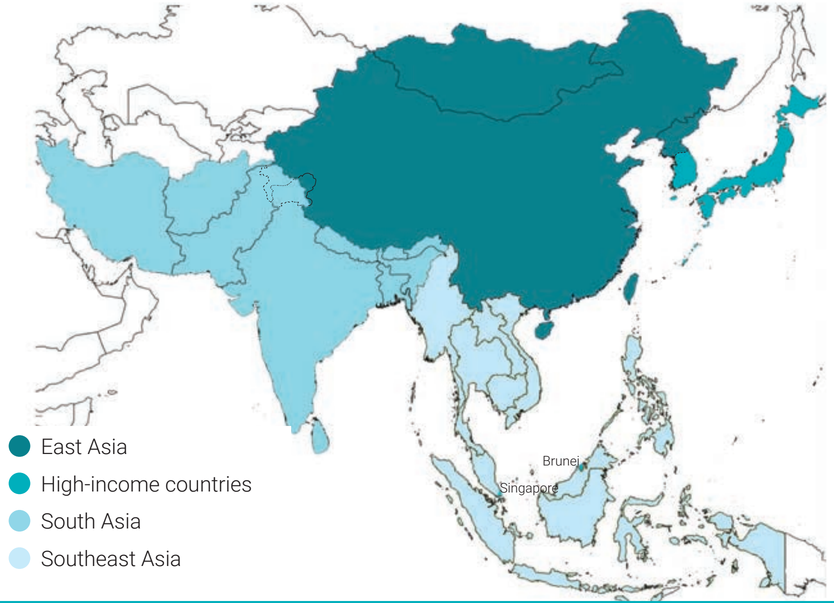


FIGURE 3: MODELLED SUB-REGIONS OF ASIA

CHAPTER 1

Why decisive action is needed to combat air pollution in Asia and the Pacific

1.1 INTRODUCTION

In this first chapter, current knowledge on air pollution impacts in the Asia and Pacific region are described and summarized in the context of international developments. These are the essential components that need to be taken into account for a comprehensive assessment of the consequences of air-polluting emissions and effective air quality management in the region. These include the effects of the major air pollutants – fine particulate matter equal to or less than 2.5 microns in aerodynamic diameter ($PM_{2.5}$) and ground-level ozone (O_3) – on human health (Section 1.2), the climate (Section 1.3), agricultural production and ecosystems (Section 1.4) and socio-economic development pathways (Section 1.5), including links to the Sustainable Development Goals (SDGs) in the countries of Asia and the Pacific. The treatment of impacts, or the countries in which they occur, is not exhaustive, but the information presented has been selected to underpin the analysis in Chapter 2 and the implementation of measures to reduce air pollution in the region in Chapter 3. Where relevant, an attempt has been made to include all the well-documented impacts of air pollution in the Asia and Pacific region and the major uncertainties, synergies and trade-offs between these are highlighted, as well as the multiple benefits that are possible through targeted mitigation of polluting emissions.

1.2 AIR QUALITY AND HEALTH IN ASIA AND THE PACIFIC

1.2.1 Introduction

Air pollution is well recognized as an important risk factor for global disease burdens and has a major impact on human health (Landrigan *et al*. 2017; Thurston and Lippmann 2015; Lippmann 2013; Loomis *et al*. 2013; Brauer *et al*. 2012), particularly among the poor and vulnerable such as the aged and children (Hajat *et al*. 2015). According to recent estimates, each year 7 million premature deaths worldwide and 215.5 million disability-adjusted life years (DALYs) are attributable to exposure to ambient and indoor air pollution, with the rapidly developing countries in Asia and the Pacific bearing much of this burden (WHO 2018; GBD 2018a; Cohen *et al*. 2017; WHO 2016; GBD 2016; GBD 2015a). While ambient air pollution is especially severe in some of the fastest-growing urban regions, the International Energy Agency (IEA) estimated for 2015 that approximately 2.7 billion people globally[1], of whom 1.9 billion live in Asia, continue to depend on burning solid fuels such as wood, coal, charcoal, crop residues and dung in their homes for cooking and heating (IEA 2016), resulting in very high levels of indoor air pollution. Consequently, the health risk posed by air pollution in the Asia and Pacific region impacts urban and rural communities, with the total mortality burden from indoor and ambient air pollution fourth behind dietary, tobacco and high blood pressure risks (GBD 2017a; GBD 2015a). In 2013, it was estimated that exposure to ambient and indoor air pollution cost the world's economy some US$ 5.11 trillion in welfare losses (World Bank 2016). In terms of magnitude, in South and East Asia and the Pacific this is equivalent to 7.4 and 7.5 per cent of those regions' gross domestic products (GDP) respectively (World Bank 2016).

Epidemiological studies conducted over the last three decades have established robust associations between long-term exposure to ambient and indoor air pollution and premature mortality associated with, for example, ischemic heart disease, stroke, chronic respiratory diseases and lung cancer, thereby substantially reducing life expectancy (Lippmann *et al*. 2013; Anderson *et al*. 2012; Pope *et al*. 2008). Morbidity from such conditions as chronic respiratory symptoms, including bronchitis and asthma, and from cataracts – although less serious when compared to mortality – also constitute some of the most deleterious effects of air pollution. In addition, a growing body of literature points to the special vulnerability of children to air pollution, with premature deaths from pneumonia. Additional effects on children's rapidly developing respiratory, neurological and immune systems are thought to persist well into adulthood (UNICEF 2016).

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[1] Estimates and definitions of global solid fuel use vary. For 2015, IEA estimated 2.5 billion solid fuel users; this estimate does not include coal, which adds approximately 200 million additional households worldwide. The Health Effects Institute and Institute for Health Metrics and Evaluation estimate 2.45 billion in 2015, including coal use (HEI 2018); and the World Health Organization (WHO) estimates nearly 3 billion in 2012 (WHO 2016), including coal use. IEA estimates are used for modelling in Chapter 2 and are reported here for consistency.

An expanding body of evidence points to both short-term consequences of exposure to air pollution (Luo *et al*. 2015; Shah *et al*. 2015) and a number of areas of growing concern, including fertility and birth-related outcomes (Malley *et al*. 2017; Frutos *et al*. 2015; Amegah *et al*. 2014; Stieb *et al*. 2012; Shah and Balkhair 2011), neurocognitive effects (Babadjouni *et al*. 2017; Cacciottolo *et al*. 2017; Chen *et al*. 2017b; Perera 2017; Brockmeyer and D'Angiulli 2016; Casanova *et al*. 2016; Clifford *et al*. 2016; Heusinkveld *et al*. 2016; Kioumourtzoglou *et al*. 2016; Levy 2015; Perera *et al*. 2014) and diabetes (Cosselman *et al*. 2015; Eze *et al*. 2015; Meo *et al*. 2015; Thiering and Heinrich 2015; Krewski *et al*. 2009).

Drawing on currently available epidemiological studies, particularly on chronic population exposure, $PM_{2.5}$ has served as the most consistent and robust predictor of mortality in studies of long-term exposure to air pollution. Ground-level O_3, a gas produced through atmospheric reactions of precursor emissions in the presence of sunlight (Figure 2, Introduction), has also been associated with mortality and respiratory disease independent of exposure to $PM_{2.5}$ (Atkinson *et al*. 2016).

A considerable number of epidemiological studies, mostly time series, on acute exposure to air pollution ranging from days to weeks have been carried out in the region, showing similar effects on premature mortality as studies carried out in North America and Europe. However, the health effects of acute episodic events, such as forest fires or dust storms, are yet to be described by solid scientific research in Asia and the Pacific.

This section provides a regional overview of: i. population exposure profiles and trends for $PM_{2.5}$ and O_3 in relation to World Health Organization (WHO) air quality guidelines; ii. estimates of attributable burden of disease from the 2012 WHO and 2016 Institute for Health Metrics and Evaluation (IHME) Global Burden of Disease (GBD) assessments; and iii. estimates of risks from recent short-term time series and a few long-term cohort studies from across countries in Asia and the Pacific.

These sections give the context for the modelling efforts described in Chapter 2 that estimate the expected population $PM_{2.5}$ exposure reductions and associated health benefits of alternative emission control strategies for air pollution throughout the region. This section underlines the fact that there is now sufficient evidence for action to reduce the impacts of air pollution on human health in Asia and the Pacific.

1.2.2 Estimates of population exposure to air pollution

The majority of epidemiologic research on exposure to air pollutants is based on ambient air quality data from ground-based monitoring networks. Estimates of ambient air quality concentrations from the WHO database on air pollution currently are made up of ground-level measurements from 500 cities in the Asia and Pacific region[2]. These indicate that the region contains 17 of the 30 most polluted cities in the world, although the extent and quality of air pollution monitoring data informing this database vary widely by city, country and sub-region.

Air pollution is not just a problem in cities. Nearly 2.7 billion people around the world, of whom more than 1 billion live in the Asia and Pacific region, primarily in rural communities, are exposed to extremely high concentrations of $PM_{2.5}$, carbon monoxide (CO) and a range of other air toxics, including volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs) and heavy metals, from the use of solid fuels such as wood, charcoal, coal and dung in their homes for cooking and heating (IEA 2016; Bonjour *et al*. 2013). Unlike ambient air pollution, where monitoring networks exist, data on indoor air pollution exposure are only available from a relatively limited number of research studies (Balakrishnan *et al*. 2011). Further complicating the issue are additional sources of air pollution, including open burning of solid waste and refuse (Kodros *et al*. 2016) and global shipping (Liu *et al*. 2016), that may contribute to ill-health.

To provide an overview of air pollution levels across countries, particularly in the rapidly developing urban areas of low- and middle-income countries,

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[2] see: http://www.who.int/phe/health_topics/outdoorair/databases/en/

and the large rural and suburban areas that lack any air quality monitoring stations, researchers apply a consistent methodology (Cohen *et al*. 2017) to estimate exposure to ambient and indoor air pollution. Descriptions of the global ambient and indoor air pollution models are provided in Annex 1.1.

1.2.3 Trends in exposure to ambient and indoor air pollution

1.2.3.1 Exposure to ambient air pollution

The GBD study estimates that in 2016 the population-weighted annual mean concentration of $PM_{2.5}$ in the Asia and Pacific region was 58 micrograms per cubic metre (μg/m^3), with a majority of the population living in areas exceeding the WHO Interim Target 1 of 35 μg/m^3. The population-weighted annual mean concentration using population density is used in these studies as it is more representative of the population exposure to $PM_{2.5}$ than monitoring data (Brauer *et al*. 2016; van Donkelaar *et al*. 2016). Compared to a global population-weighted annual mean concentration of 51 μg/m^3 and the 58 per cent of the global population that lives in areas that exceed WHO Interim Target 1, it is clear that the population of Asia and the Pacific is among the most highly exposed to $PM_{2.5}$ in the world (Figure 1.1).

Long-term trends for $PM_{2.5}$ and ozone

There was an estimated 19 per cent increase in annual population-weighted $PM_{2.5}$ concentrations in the Asia and Pacific region between 1990 and 2015, with many countries experiencing an increase in population exposure (HEI 2018). The rates of increase within the region exceeded the 10 per cent global increase during this same period (Figure 1.2). Ozone concentrations were also estimated to have increased at a greater rate throughout South Asia than globally.

1.2.3.2 Exposure to indoor air pollution

Globally, average daily particulate matter concentrations in homes burning solid fuels

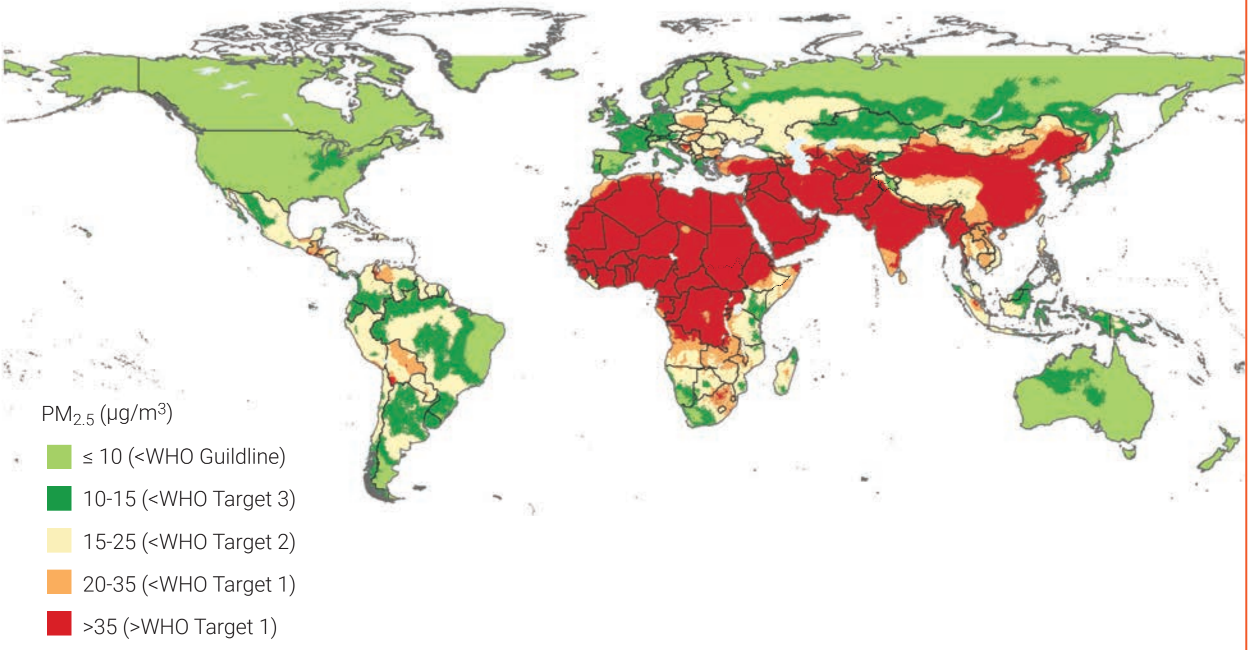
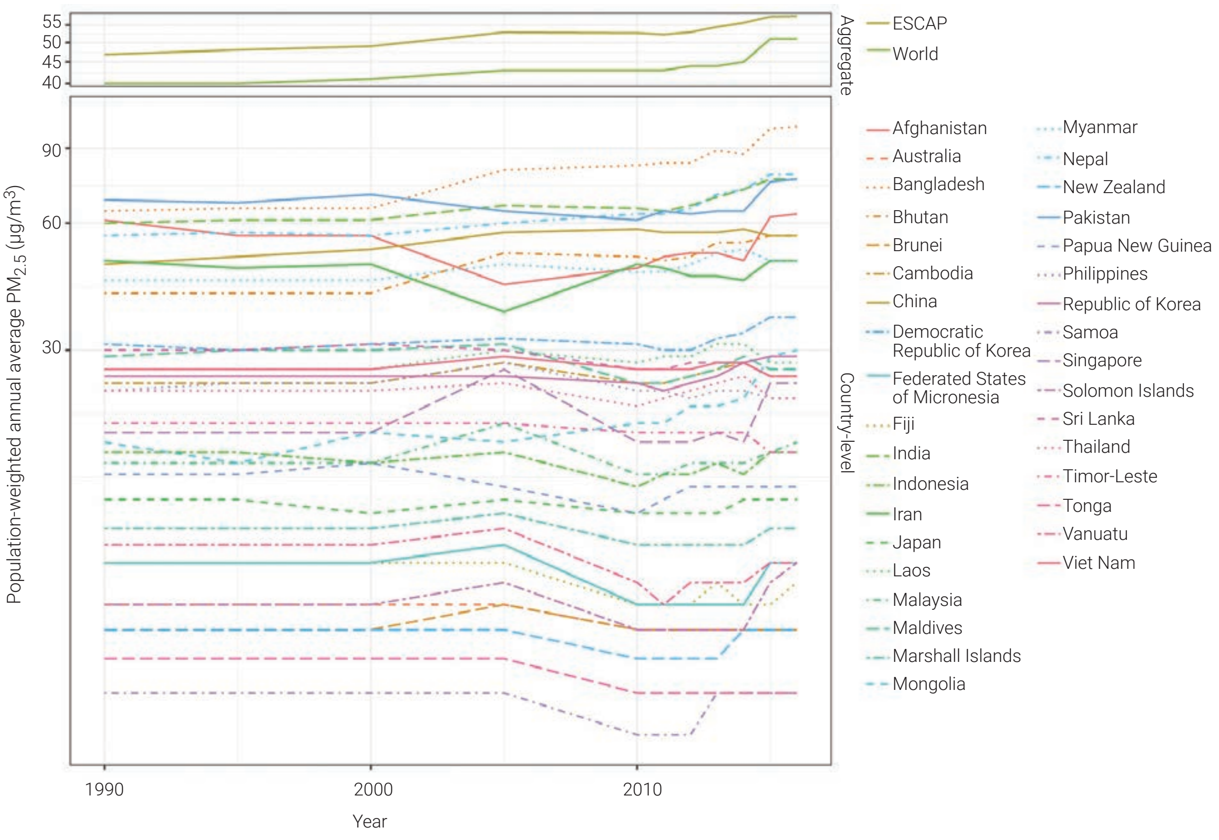


FIGURE 1.1: COMPARISON OF ANNUAL AVERAGE $PM_{2.5}$ POPULATION-WEIGHTED CONCENTRATIONS IN 2016 WITH WHO AIR QUALITY GUIDELINES

Source: HEI 2018



Note: The aggregate panel shows the global trend.

FIGURE 1.2: TRENDS IN ANNUAL AVERAGE POPULATION-WEIGHTED $PM_{2.5}$ EXPOSURE TO AMBIENT AIR POLLUTION IN ASIA AND THE PACIFIC, 1990–2015

Source: Adapted from data available from State of Global Air 2018 (stateofglobalair.org)

have been reported to range between 300 and 3,000 µg/m_3 (Clark *et al*. 2013; Balakrishnan *et al*. 2011). The distribution of exposures is heterogeneous and complex, with multiple determinants, such as the fuel/stove type, kitchen area ventilation, quantity of fuel, age, gender and time spent near the cooking area, influencing spatial and temporal patterns of exposure within and between households. Regardless of the variability in results across studies and within and between countries, however, there is unequivocal evidence of extreme exposure in all communities that use solid cooking fuel, often many times higher than the recommended WHO guidelines for ambient and indoor air quality intended to protect public health – the guidelines for daily mean $PM_{2.5}$ and particulate matter equal to or less than 10 microns in aerodynamic diameter (PM_{10}) are 25 µg/m^3 and 50 µg/m^3, respectively (WHO 2006).

While the proportion of households relying on solid cooking fuels has decreased over the last few decades (Figure 1.3), this has been offset in some but not all countries by a simultaneous increase in population (Bonjour *et al*. 2013), resulting in the number of people using solid cooking fuels remaining nearly the same.

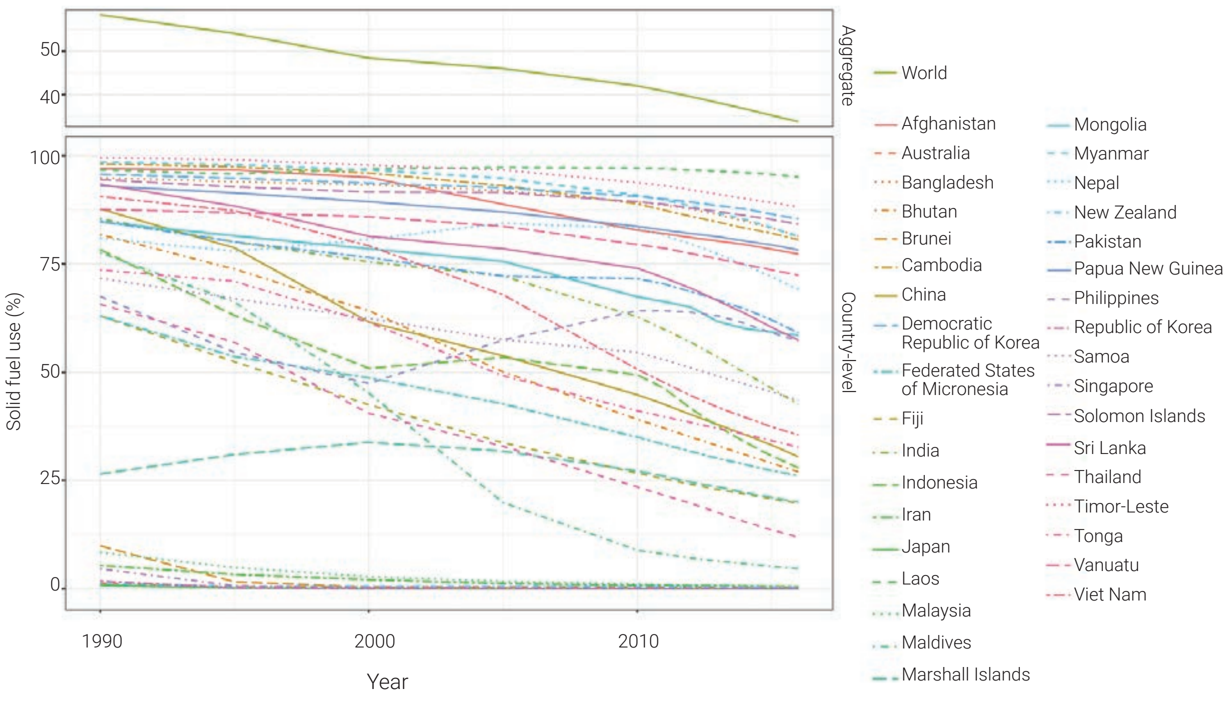
1.2.4 Estimating the health burden attributable to air pollution

The GBD study relies on the use of integrated exposure-response (IER) functions to generate consistent risk estimates across the four major categories of combustion particle exposures – indoor air pollution, ambient air pollution, active tobacco smoking, and second-hand tobacco smoke (SHS). The IER functions have been modelled relating $PM_{2.5}$ exposure to specific diseases – ischemic heart disease, stroke, lung cancer, adult chronic obstructive pulmonary disease and child acute lower respiratory infections (Cohen *et al*. 2017; Burnett *et al*. 2014). The IER functions are based on an exponential decay model that does not constrain the relationship between concentration and outcome to the linear. Additionally, the modelling allows the evidence from epidemiological studies concerning any of the categories of combustion particles to be pooled using the daily dose of $PM_{2.5}$ as the primary exposure metric (Annex 1.1).

1.2.4.1 Health impacts

Air pollution – indoor and ambient $PM_{2.5}$ air pollution – is associated with 7 million premature deaths each year globally (WHO 2018; GBD 2018a; GBD 2017a; WHO 2016; GBD 2015a). In 2012, low- and middle-income countries in the Western Pacific and Southeast Asia regions (as defined by WHO 2016) had the highest age-standardized death rate per 100,000 people – 65 and 59, respectively (Figure 1.4).

It is important to note that current methods of calculating the health impact of ambient air pollution assume that windblown dust affects health the same way as $PM_{2.5}$ from other sources. The health



Note: The aggregate panel shows the global trend.

FIGURE 1.3: CHANGE IN THE PERCENTAGE OF HOUSEHOLDS RELIANT ON SOLID FUELS FOR COOKING IN ASIA AND THE PACIFIC

Source: Adapted from data available from State of Global Air 2018 (stateofglobalair.org) impacts associated with these exposures, while not yet fully understood, are currently treated in the same way as those from air pollution in industrialized countries where most of the epidemiological studies have been performed. There is a need for a better assessment of the health impacts of this dust, as it could result in much lower burdens than those from anthropogenic particulate matter (WHO 2016). Further, during periods of intense atmospheric haze, initial mortality estimates indicate a potentially high burden (Koplitz *et al*. 2016). More research is needed on the health impacts of windblown dust and haze.

Health responses to air pollution vary due to gender-linked biological differences and gender-based determinants of activity patterns and exposure (Clougherty *et al*. 2010). Indoor air pollution was estimated to be responsible for 4.3 million deaths in 2012 (WHO 2014); the mortality associated with air pollution in 2016 by type of air pollution in the Asia and Pacific region is shown in Figure 1.5. Indoor air pollution is gender-shifted to women and young girls who tend to spend more time indoors. This is particularly the case in Asian and African countries where gender roles are still observed – women are expected to stay at home, take care of children or other family members, and especially to prepare and cook meals (WHO 2016; Clougherty *et al*. 2010).

In poor rural areas of developing countries where there is limited access to clean energy and alternative stoves, the main source of indoor air pollution is cooking combustion, which produces black carbon (BC), PAHs, $PM_{2.5}$ and other toxic pollutants. Women involved in cooking experience some of the highest levels of air pollution exposure (Balakrishnan *et al*. 2013a). Burning solid fuels for cooking is a major cause of mortality in low- and middle-income countries (Cohen *et al*. 2017) and in 2012, 60 per cent of all premature deaths from indoor air pollution were observed in women and children (WHO 2016). In addition to substantial health impacts associated with chronic exposure, women also bear significant burdens associated with time spent in fuel collection as well as safety concerns associated with the use of solid-fuel stoves and during fuel collection (Bloomfield *et al*. 2015).

As women spend the most time exposed to indoor sources, they are at highest risk. If the woman is pregnant, the risks are heightened and also extended to the foetus, as proven by several studies linking indoor air pollution with preterm and low-weight births (Balakrishnan *et al*. 2017; Malley *et al*. 2017; Amegah *et al*. 2014; Stieb *et al*., 2012; Shah and Balkhair 2011).

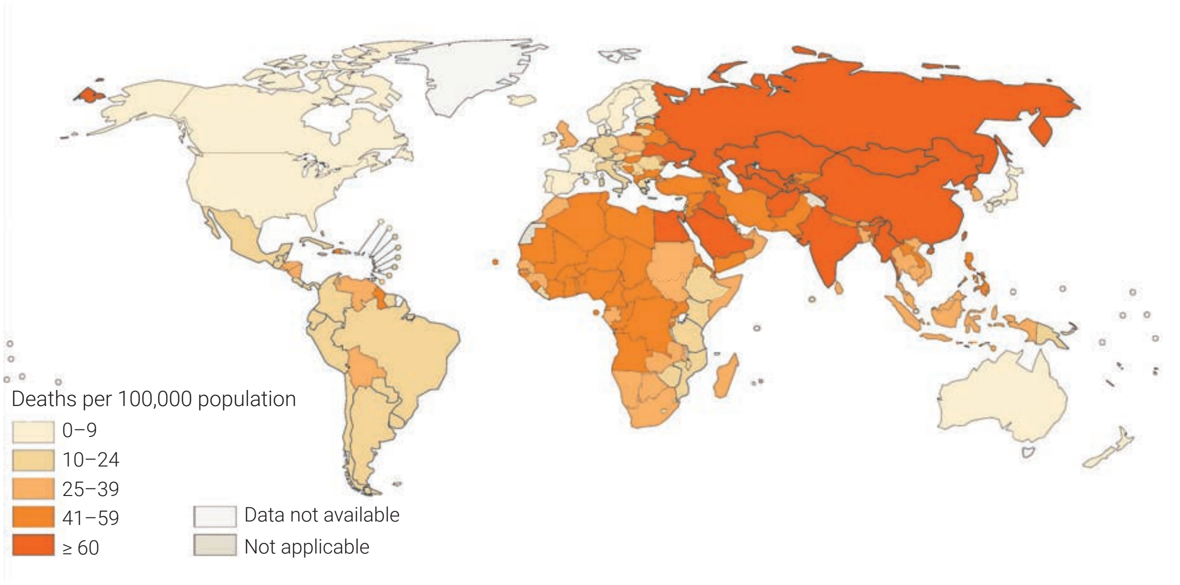


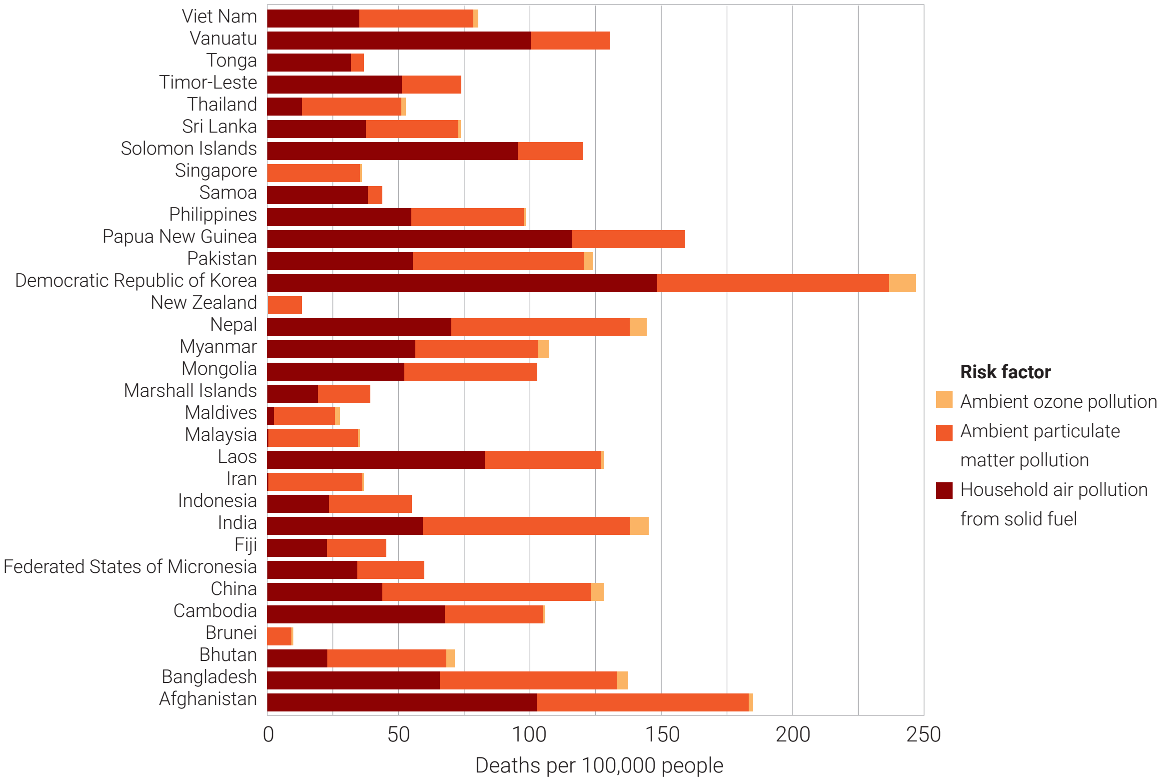
FIGURE 1.4: AGE-STANDARDIZED DEATHS PER 100,000 PEOPLE ASSOCIATED WITH AIR POLLUTION, BY COUNTRY, 2012

Source: adapted from WHO 2016

Consequently, young children staying in the house, or strapped to their mothers, are also exposed to hazardous indoor pollutants. According to the WHO (2016), exposure to indoor air pollution can also be strongly influenced by cultural attitudes towards gender: in general girls spend more time in the kitchen (e.g. Armstrong and Campbell 1991) but there are cultural exceptions, for example, boys in India have been shown to be cared for longer, spending more time in the kitchen and therefore have higher chances of developing acute respiratory infections (Matinga 2010; Mishra 2001).

The gender paradigm for indoor air pollution health impacts is very much coupled with socio-economic status and cultural influences, with women generally spending more time indoors and thus being at the greatest potential risk. Women are, however, also key in alleviating the problem for their families and themselves. Education can encourage them to choose the less polluting stoves and fuel, or position stoves to maximize smoke/pollutant dispersion.

Beyond the direct effects of indoor air pollution on exposure and human health, a growing body of evidence indicates that it has substantial impacts on ambient air pollution. This evidence – based largely on modelled estimates, though backed up by source apportionment and other evidence – indicates that a substantial portion of ambient air pollution arises from indoor sources, though there is wide global heterogeneity. In India, for example, seven evaluations of the contribution of households to ambient air pollution estimate it at 22–52 per cent (Conibear *et al*. 2018; GBD 2018b; Butt *et al*. 2016; Silva *et al*. 2016; Lelieveld *et al*. 2015; Chafe *et al*. 2014; see also http://www.urbanemissions.info/). A 2016 estimate from the Health Effects Institute (HEI), based on the methodology of the GBD study (GBD 2015b), showed that 25 per cent of deaths attributed



Note: there is some overlap between indoor and ambient air pollution.

FIGURE 1.5: MORTALITY ASSOCIATED WITH AIR POLLUTION IN THE ASIA AND PACIFIC REGION, BY COUNTRY, 2016

Source: adapted from GBD Compare, IHME 2017 to $PM_{2.5}$ exposure – nearly 270,000 – arise from the contribution of households to ambient pollution.

According to these estimates, household biomass burning was the largest single contributor to ambient air pollution in India. Similarly, the HEI reported that for China, household solid fuel combustion contributed to approximately 177,000 deaths in 2013 and was an important contributor to ambient air pollution (GBD 2016). These findings, along with those from other studies relating household air pollution to ambient air pollution, indicate that cleaning up household combustion will be required to substantially improve global ambient air quality.

1.2.4.2 Regional studies on the health effects of air pollution

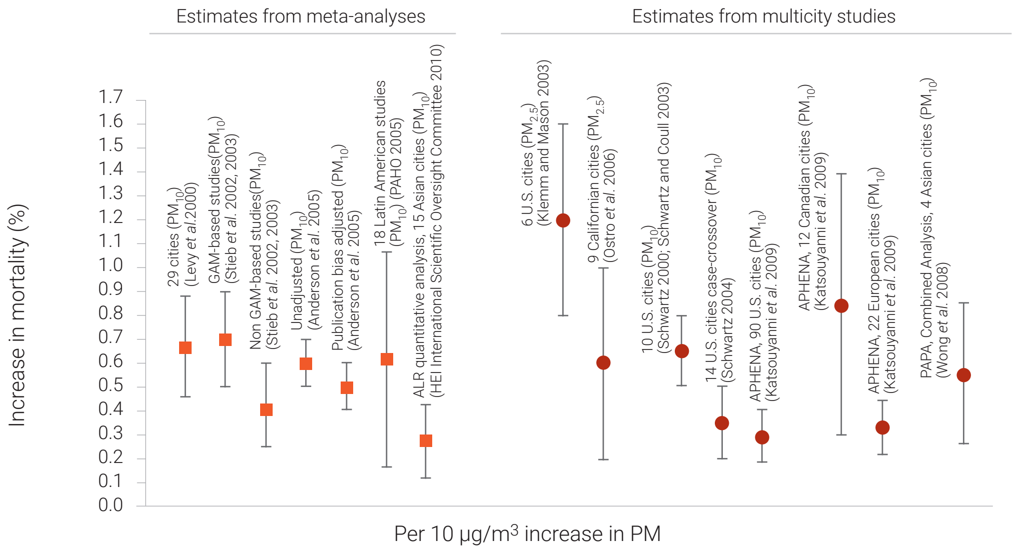
Much of the current evidence used for assessments of the disease burden related to air pollution relies on long-term cohort studies mostly conducted in North America and Europe over multiple years. This evidence is included in the IER approach to estimate excess risks (Cohen *et al*. 2017; Burnett *et al*. 2014) of mortality and morbidity associated with exposure to $PM_{2.5}$. However, even prior to the development of disease burden assessment methods, time-series studies of the effects of short-term exposure (days to weeks) on morbidity and mortality from cardiovascular and/or respiratory diseases have provided consistent evidence of the adverse health effects of air pollution, informing policies in North America (Samet *et al*. 2000; Greenbaum 2001) and Europe (Samoli *et al*. 2008). Based on this experience, a growing number of time-series studies have also been conducted in Asia and reported in meta-analyses and reviews (Atkinson *et al*. 2011; HEI 2010) as well as in findings from large and coordinated multi-city studies that have explored associations between exposure to air pollution and cardiovascular, respiratory and other outcomes (Siddharthan *et al*. 2018; Yu *et al*. 2018; Chen *et al*. 2017a; Wong *et al*. 2016a, 2016b; Yin *et al*. 2017a, 2017b, 2017c; Yorifuji *et al*. 2015; Dholakia *et al*. 2014; Balakrishnan *et al*. 2013b; Nishiwaki *et al*. 2013; Qian *et al*. 2013; Yorifuji *et al*. 2013; Rajarathnam *et al*. 2011; Kumar *et al*. 2010; Kan *et al*. 2008; Vichit-Vadakan *et al*. 2008; Wong *et al*. 2008).

The meta-analysis of time-series studies in Asia (Atkinson *et al*. 2011) identified 115 studies that found consistency between the risk estimates for short-term air pollution exposure, mortality and morbidity reported in Asian studies and studies in other parts of the world (Pope and Dockery 2006) (Figure 1.6). This finding is both remarkable and important given the substantially greater annual average particle concentrations found in the large Asian cities compared to North American and European cities. Similarly, the results for short-term O_3 exposure align broadly with those from other parts of the world (Figure 1.7).

A recent multi-city assessment in China (Yin *et al*. 2017c) estimated the associations between PM_{10} concentrations and daily mortality from cardiorespiratory and non-cardiorespiratory diseases and all other causes for 38 large cities in China, with mean daily PM_{10} concentrations across all cities of 92.9 $\mu g/m^3$. Meta-analyses suggested that on average a 10 $\mu g/m^3$ increase in concurrent-day PM_{10} was associated with a 0.44 per cent increase in the daily number of deaths, a result that is comparable to other large-scale meta-analyses involving some 33 other independent time-series and case cross-over studies in China (Shang *et al*. 2013). PM_{10} had a larger impact on people with cardiorespiratory diseases, the old and women. The PM_{10} effect also depended on demographic socio-economic conditions in different cities.

Finally, a recent Chinese prospective cohort study, one of the first in Asia, of nearly 190,000 men over the age of 40 used the annual average $PM_{2.5}$ levels developed for the GBD 2013 study to estimate risk of non-accidental cardiovascular disease, chronic obstructive pulmonary disease and lung cancer mortality. The study compared its results with the risk estimates predicted by the IER function built largely on North American and Western European data.

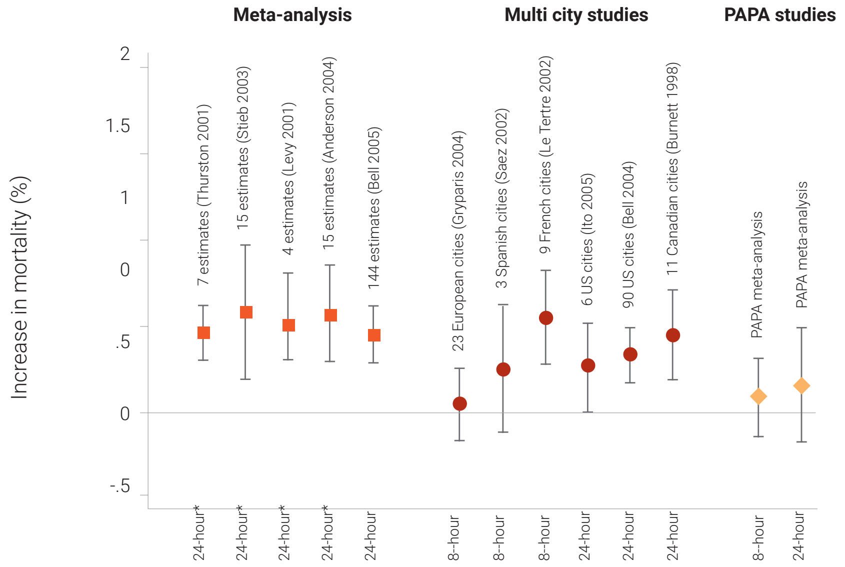
The study found that long-term exposure to $PM_{2.5}$ was consistently associated with non-accidental mortality, cardiovascular disease, lung cancer and chronic obstructive pulmonary disease mortality in China. It was one of the first to address exposure across both urban and rural settings. The study reported that the IER estimator may underestimate



Note: recent understanding of health impacts concerns $PM_{2.5}$ and there is uncertainty converting between PM_{10} and $PM_{2.5}$. In the absence of $PM_{2.5}$ studies, PM_{10} studies show similar results for Asia and the rest of the world.

FIGURE 1.6: COMPARISON OF PM_{10} RESULTS FROM US AND EUROPEAN META-ANALYSES, MULTI-CITY STUDIES AND ASIAN SYSTEMATIC REVIEWS

Source: HEI 2010 and references therein



Note: the random effects estimate for all-causes mortality was 0.07 per cent (95 per cent confidence interval, −0.16 per cent, 0.30 per cent) per 10 µg/m³ increase in O_3 over eight hours.

FIGURE 1.7: COMPARISON OF INCREASES IN MORTALITY FROM OZONE RESULTS FROM US AND EUROPEAN META-ANALYSES, MULTI-CITY STUDIES, AND THE ASIAN SYSTEMATIC REVIEWS

Source: HEI 2010 and references therein

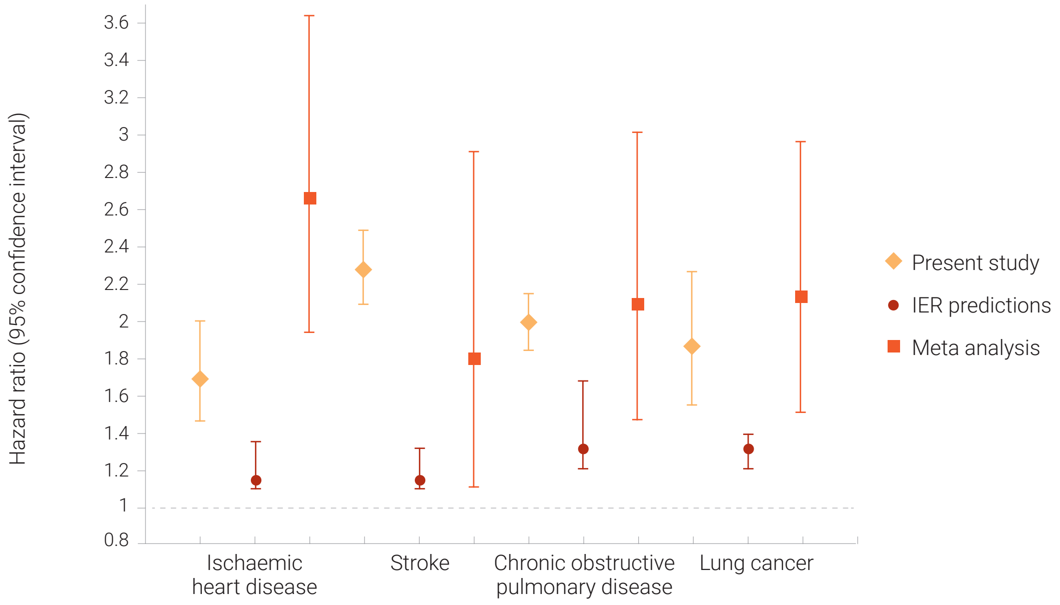
mortality due to the long-term exposure to $PM_{2.5}$ over the higher exposure ranges experienced in China and other low- and middle-income countries (Figure 1.8).

1.2.5 State of knowledge and uncertainty

While most health burden assessments, including the GBD, utilize the most recent accessible datasets on mortality and disease incidence as provided or corroborated by in-country collaborators, in many instances these are limited by the completeness and accuracy of the available datasets. Improvement in the disease and cause of death registries can substantially reduce uncertainties in burden assessments at the national and regional scales.

Considering differences in ethnicity, lifestyle, the role of windblown dust, season and weather, amongst other factors, between the Asian and European/American regions, it is especially important to select the appropriate exposure-response function. There is considerable consistency between the risk estimates obtained from short-term epidemiological studies for $PM_{2.5}$ and O_3 in Asia and those currently available from studies primarily of areas outside the region. However, there is a need to undertake more epidemiological studies, such as cohort studies, for O_3 and $PM_{2.5}$ in Asia, and to address potential uncertainties resulting from underlying region-specific differences in ethnicity; pollutant mixtures, including the role of wind-blown dust in many countries; nutritional status; and other disease-specific co-variates. This will greatly enhance the accuracy of the risk estimates obtained from exposure-response relationships. Furthermore, improvements in locally available mortality and morbidity datasets are crucial in being able to improve on health impact estimates that currently attribute millions of premature deaths to air pollution in Asia.

The Global Burden of Disease methodologies, for example of WHO, IHME and Environmental Benefits Mapping and Analysis Program of the USEPA (BENMap), play a key role in identifying the factors that contribute most to disease and mortality – the first step towards identifying what can be done to improve public health. Among the 79 risk factors included in its comprehensive analysis, the GBD project reported that exposure to ambient and indoor



Note: Hazard ratios are calculated based on exposures at the 5th (15.5 ug/m^3) and 95th (77.1 ug/m^3) percentile using three methods/data sources: Yin *et al.* 2017a, IER predictions (Cohen *et al.* 2017), and previous Meta analysis.

FIGURE 1.8. COMPARISON OF CAUSE-SPECIFIC HAZARD-RATIO ESTIMATES: IN A STUDY OF CHINESE MEN OVER THE AGE OF 40

Source: Yin *et al.* 2017a

air pollution from $PM_{2.5}$ was the highest-ranking risk factor among environmental factors contributing to mortality. Furthermore, the use of solid cooking fuels can have significant gender- and livelihood-related impacts for women, in addition to the direct health impacts. The GBD project has also laid out the critical interplay between trends in population structure, underlying disease, economic factors and trends in air pollution. Knowledge of these trends is essential for understanding patterns in the burden of disease experienced by the populations of different countries and regions and for helping to inform decision makers on where policy action to reduce population exposure at the national or regional level has the most potential to provide large benefits in improved health.

There are methods for estimating disease burdens associated with risk factors such as air pollution and for comparing these estimates with those made for other risks. While a specific exercise for the Asia and Pacific region would be best for guiding policy decisions, there is currently not enough data from the region, especially epidemiologic data of the type needed, to associate exposure to air pollution with various health outcomes. Thus, while the lack of region-specific data leads to some uncertainty, this should not prevent immediate action to control air pollution, especially in light of the large and consistent global evidence base.

Further, the broad consistency in results from short-term health effects studies conducted across North America, Europe and Asia and newly reported long-term cohort studies from China provide a very coherent argument for large and dual health burdens from ambient and indoor air pollution in the region. China and India have also recently launched sub-national – provincial or state level – burden of disease assessments using the GBD approach (India State-level Burden of Disease Collaborators 2017), indicating a broader willingness for governments in the region to use the GBD approaches to foster air quality action.

The differences between alternative modelling approaches are minor in the face of the large burdens that confront populations. The preceding sections provide a compelling rationale for acknowledging the imminent need for air quality action in most countries in the region. This section is intended to serve as a prelude to the modelling efforts described in Chapter 2 that compare and contrast multiple scenarios of air quality action that can result in health gains.

1.2.6 Conclusions

- According to recent estimates, each year 7 million premature deaths worldwide are attributable to exposure to ambient and indoor air pollution, with the rapidly developing countries in Asia and the Pacific bearing much of this burden.

- Around 1.9 billion people living in Asia depend on burning solid fuels for cooking and heating, which is a major cause of mortality in low- and middle-income countries with women and children particularly affected.

- A number of studies indicate that reducing emissions from household cooking and heating may also be required to substantially improve ambient air quality in some parts of Asia and the Pacific.

- The total mortality burden from indoor and ambient air pollution is ranked fourth behind dietary risks, tobacco and high blood pressure. In 2013, it was estimated that exposure to ambient and indoor air pollution cost the world's economy about US$ 5.11 trillion in welfare losses. In South and East Asia this cost is equivalent to 7.4 and 7.5 per cent of their GDP respectively.

- An expanding body of evidence points to a number of areas of growing concern, including fertility and birth-related outcomes neurocognitive effects and diabetes related to exposure to air pollution.

- In 2016, the population-weighted annual mean concentration of $PM_{2.5}$ in the Asia and Pacific region was estimated to be 58 $\mu g/m^3$, with a majority of the population living in areas exceeding the WHO Interim Target 1 of 35 $\mu g/m^3$.

- There is considerable consistency between the risk estimates obtained from short-term epidemiological studies for $PM_{2.5}$ and O_3 in

Asia and those currently available from studies primarily of areas outside the region.

- There is a need to undertake more epidemiological studies, such as cohort studies, for O_3 and $PM_{2.5}$ in Asia, and to address potential uncertainties resulting from underlying region-specific differences in ethnicity and pollutant mixtures, including the role of wind-blown dust in many countries.

1.3 AIR QUALITY AND CLIMATE

1.3.1 Introduction

Air quality and climate change are closely related (Fiore *et al*. 2015; Fuzzi *et al*. 2015; Monks *et al*. 2015; Stohl *et al*. 2015; von Schneidemesser *et al*. 2015; Shindell *et al*. 2012; UNEP/WMO 2011; Isaksen *et al*. 2009). Key greenhouse gases, such as carbon dioxide (CO_2) and methane (CH_4), and air pollutants including short-lived climate pollutants (SLCPs), share many emission sources and are often emitted together from the same tailpipe or smokestack, for example diesel vehicles and coal plants. It is thus widely recognized that improving air quality can make a sizable contribution to tackling climate change problems, for instance fuel efficiency improvements decreasing air pollutant and CO_2 emissions.

Future changes in climate are known to affect air quality by influencing the formation and removal processes of ground-level O_3 (Figure 2, Introduction) and aerosols through changes in temperature, precipitation, other meteorological conditions and precursor concentrations (Allen *et al*. 2016; Jacob and Winner 2009). Links between air quality and climate change are immensely complex and an active area of scientific research.

Understanding the interplay between air quality and climate change is key for designing integrated policies and plans that maximize air quality and climate co-benefits. This section focuses on the physical and biogeochemical aspects of such connections. Section 1.3.2 provides a short overview of how air pollution influences global climate change. The impacts on the Asian cryosphere and monsoons are discussed in sections 1.3.3 and 1.3.4, respectively. The climate impacts on air pollution are described in section 1.3.5 and climate-related discussions on SLCP mitigation strategies and issues associated with interactions between climate and air quality policies in section 1.3.6. Conclusions are given in section 1.3.7. Regional haze in different parts of Asia and winter fog in South Asia are introduced in Boxes 1.2 and 1.3 respectively.

1.3.2 Global climate impacts of air pollutants

There is a wealth of evidence that anthropogenic emissions of aerosol particles, such as BC and organic carbon (OC), and gaseous pollutants such as sulphur dioxide (SO_2), CO, VOC and oxides of nitrogen (NO_x), that act as precursors for the atmospheric formation of O_3 and secondary aerosol particles, affect the climate (IPCC 2013; Myhre *et al*. 2013b). As well as affecting climate, secondary aerosol particles formed in the atmosphere, such as organic, sulphate, nitrate and ammonium aerosol, are also important components of $PM_{2.5}$ affecting human health (section 1.2) and ecosystems (section 1.4).

Ozone is formed in the atmosphere from the interaction of CO, NO_x, CH_4 and VOCs in the presence of sunlight (Figure 2, Introduction). Methane is itself a strong greenhouse gas, as is O_3, adding to the warming of the atmosphere. The other O_3 precursors – CO, VOCs, NO_x – do not directly influence the climate but do so indirectly by contributing to the formation and depletion of tropospheric O_3 and CH_4 (Myhre *et al*. 2013b).

Aerosols affect the climate through several key mechanisms. They directly impact the climate by scattering, for instance by sulphate and organic aerosols, or absorbing, for example by BC aerosols, incoming radiation from the sun and outgoing radiation from the Earth. They indirectly influence the climate by changing cloud properties –cloud droplets, cloud reflectivity and lifetimes. Furthermore, light-absorbing aerosol particles, when deposited on snowfields and glaciers, make the surface darker, changing the surface albedo, with the result that more sunlight is absorbed, affecting climate and the melting of snow and glaciers (section 1.3.3). Although uncertainties are large, it is well established that, at the global scale, the net effect of total aerosols is cooling (Boucher *et al*. 2013).

With the notable exception of CH_4, which is globally dispersed, the air pollutants discussed here are not well-mixed at the global level; they remain more concentrated in and around the source region, meaning that their climate impacts depend on the location of emissions (Collins *et al*. 2013; Lund *et al*. 2012; Berntsen *et al*. 2006). Note also that the focus here is on air pollutants emitted by human activities because of direct policy relevance to reducing emissions and impacts; no natural emissions are covered unless required. It should, however, be noted that natural aerosols also affect the climate directly or indirectly as mentioned above (Carslaw *et al*. 2013).

The rest of section 1.3.2 provides an overview of current understanding of the radiative forcing and temperature impacts of air pollutants at the global level. The following components of air pollution are considered in this section: gaseous species – CO, VOCs, NO_x, NH_3, CH_4 and tropospheric O_3; and aerosols – sulphate, nitrate, ammonium, BC, brown carbon (BrC), other OC and secondary organic aerosols (SOA). While radiative forcing on a species level is discussed, when it comes to the measures explored in Chapter 3, it is important to consider the net effect of the mix of species emitted together, such as BC and OC co-emitted from biomass burning. Hydrofluorocarbons (HFCs) are also included in this report. Although HFCs are not regarded as air pollutants, they are emitted in significant quantities and have a considerable impact on climate forcing (warming) (Figure 1.9 and Box 1.1)

1.3.2.1 Radiative and temperature impacts of different pollutants

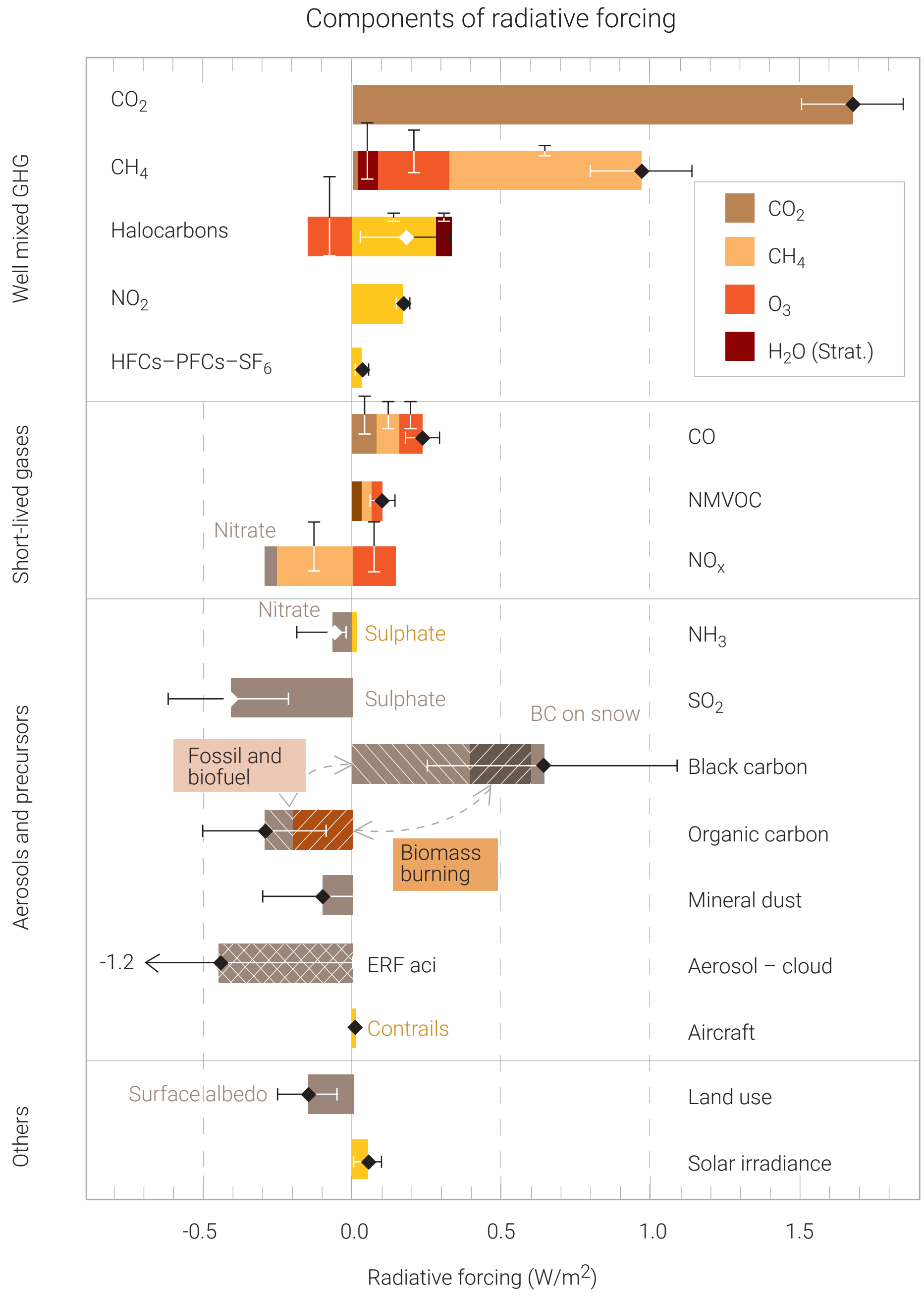
The present knowledge of the global magnitude of radiative forcing of each component is shown in Figure 1.9. Radiative impacts of gaseous pollutants – CO, non-methane volatile organic compounds (NMVOCs), and NO_x – are generated indirectly through changes in tropospheric O_3 and CH_4 via hydroxyl radical (OH) chemistry (Monks *et al*. 2015; Stevenson *et al*. 2013). Carbon monoxide and VOC emissions result in an increase in tropospheric O_3 and CH_4 concentrations as well as CO_2 concentrations through oxidation, leading to warming. Conversely, the temperature impact of NO_x depends on the timescale of interest (Figure 1.10).

BOX 1.1: HYDROFLUOROCARBONS

Hydrofluorocarbons are a group of powerful factory-made greenhouse gases used primarily for refrigeration and air conditioning. Production, consumption and emissions of HFCs have been growing at a rate of 10–15 per cent per year, causing a doubling every five to seven years. This rapid growth is due to their use as replacements for O_3 depleting substances, which are being phased out under the Montreal Protocol, as well as increasing demand for consumer air conditioning and refrigeration. The Asia and Pacific region is one of the most significant drivers of both the demand for and supply of HFCs globally.

The use of HFCs in residential air conditioning systems has experienced significant growth over the past decade. Under current trends, an additional 700 million air conditioning units will be added to the global stock by 2030, and 1.6 billion by 2050. This rapid growth has significant implications for future HFC emissions as well as energy security and air pollution from energy generation, as air conditioning accounts for a significant percentage of peak energy loads in hot climates.

Many HFCs remain in the atmosphere for less than 15 years. Though they represent a small fraction of current total greenhouse gases (less than 1 per cent), their warming impact is particularly strong and, if left unchecked, they could account for nearly 20 per cent of climate pollution by 2050. A recent study concluded that replacing HFCs that have high global warming potential (GWP) with low-GWP alternatives could avoid 0.1°C of warming by 2050.



CO_2 – carbon dioxide

CH_4 – methane

HFCs – hydrofluorocarbons

PFCs – perfluorocarbons

SF_6 – sulphur hexafluoride

HCFCs – hydrochlorofluorocarbons

CO – carbon monoxide

NMVOCs – non-methane volatile organic compounds

NO_x – nitrogen oxides

NH_3 – ammonia

SO_2 – sulphur dioxide

BC – black carbon

ERF aci – effective radiative forcing (ERF)

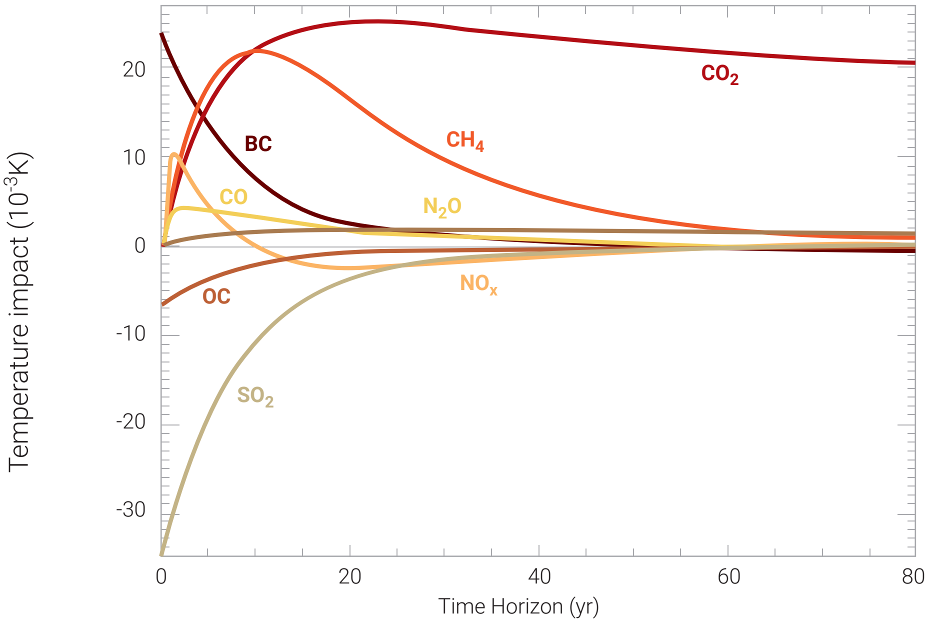
aerosol – cloud interactions (aci)

W/m^2 – watts per square metre

GHG – greenhouse gas

FIGURE 1.9: PRESENT MAGNITUDES OF THE RADIATIVE FORCING OF AIR POLLUTANTS, CLIMATE FORCERS AND OTHER CHANGES FOR THE PERIOD 1750–2011

Source: IPCC 2013 (Figure 8.17)



Note: 2008 is year 0.
The figure shows how some components have strong short-lived temperature effects of both signs while CO_2 has a weaker initial effect but one that persists to create a long-lived warming effect.

FIGURE 1.10: TEMPERATURE RESPONSE BY COMPONENT FOR TOTAL ANTHROPOGENIC EMISSIONS FOR A 1-YEAR PULSE

Source: Myhre *et al*. 2013b (Figure 8.33)

Emissions of NO_x increase tropospheric O_3 concentrations on short timescales (warming) but decrease the CH_4 concentration on decadal timescales (cooling) (Shine *et al*. 2005; Wild *et al*. 2001). Furthermore, NO_x emissions lead to the formation of nitrate aerosol, which leads to cooling. Methane itself is the second strongest greenhouse gas after CO_2 in terms of direct radiative forcing, but it also has an indirect radiative forcing effect by producing tropospheric O_3 (more warming).

As mentioned earlier, aerosols affect the radiative budget in the climate system in two ways (Myhre *et al*. 2013b): by scattering or absorbing the solar and thermal radiation (aerosol-radiation interactions), and by altering cloud properties and lifetimes (aerosol-cloud interactions). The first type of interactions for each species, which cause distinctive and sometimes opposing impacts, are mainly described here. The second aerosol-cloud interactions are known to produce negative impacts collectively, albeit with large uncertainties (Figure 1.9).

Emissions of gaseous SO_2, are precursors of sulphate aerosols that reflect the incoming radiation back to space, cooling the Earth's surface and partly masking present global warming (Andreae *et al*. 2005). Nitrate aerosols are formed through the oxidation of NO_x, contributing to cooling. Formation of nitrate aerosols is closely related to the availability of NH_3 and SO_2 (Seinfeld and Pandis 2016; Behera *et al*. 2013), and it is therefore important to consider NO_x, NH_3, and SO_2 simultaneously in clean air policies (Heo *et al*. 2016; Pinder *et al*. 2007). The magnitude of cooling from total ambient aerosols, with sulphate aerosols being most dominant, is, however, highly uncertain (Figure 1.9). Aerosol forcing uncertainties give rise to one of the major uncertainties in global climate projections on decadal and centennial timescales (Armour and Roe 2011; Tanaka and Raddatz 2011; Knutti 2008; Andreae *et al*. 2005; Harvey and Kaufmann 2002).

Another species of aerosol known to significantly influence global temperatures is BC. It is generally considered that BC contributes to warming, although this is the subject of debate and uncertainty (Stjern *et al*. 2017; Bond *et al*. 2013; Myhre *et al*. 2013a), carrying important implications for SLCP mitigation strategies (section 1.3.6). Black carbon warms the climate mainly through the direct atmospheric heating of solar radiation absorption and the reduction in surface albedo caused by deposition on snow and ice; the warming effects of BC outcompete the cooling effects from other processes – scattering, cloud albedo and cloud lifetime effects. Black carbon warming depends on its location in air: it warms the layers of the atmosphere where it is located, but that can cool the surface underneath by reducing the energy reaching the surface.

There are several other aerosol species that influence global temperatures. Some OC aerosols that are normally emitted with BC from common sources, for example biomass burning and peat fires, contribute to cooling. Brown carbon, a fraction of OC that absorbs solar radiation, has recently been recognized (Laskin *et al*. 2015) as a class of compounds that may positively revise the net radiative forcing due to organic aerosols (Feng *et al*. 2013). Secondary organic aerosols account for a substantial fraction of total aerosols in the atmosphere (Zhang *et al*. 2007), but are not included in Figure 1.9 because their formation depends on factors that are yet to be sufficiently quantified.

In summary, this section introduced the radiative and temperature impacts of air pollutants, highlighting the diversity in magnitudes, timescales and pathways of such impacts. It needs to be kept in mind that the radiative forcing of air pollutants is generally uncertain because of a variety of mechanisms involving a suite of chemical species operating on different spatial and temporal timescales. The net effect of these impacts on the climate is, however, generally understood within accepted uncertainty bounds (IPCC 2013).

1.3.2.2 Effects on precipitation

Changes in temperature and incoming solar radiation affect global precipitation by altering the hydrological cycle. Precipitation impacts are generally more uncertain than global temperature impacts. A robust precipitation response to warming, caused by greenhouse gas emissions or a decrease in light-scattering aerosols, is that global precipitation increases by 1–3 per cent per degree centigrade (°C) of warming (Held and Soden 2006). Another robust response with regard to precipitation patterns is that wet areas become wetter, while dry regions become drier (Samset *et al*. 2018; Samset *et al*. 2016; Allen and Ingram 2002).

Precipitation responds differently from warming when it is caused by absorbing BC and BrC aerosols because of different mechanisms involving direct atmospheric heating (Andrews *et al*. 2010; Ming *et al*. 2010). Both light-absorbing and light-scattering aerosols such as sulphate aerosols decrease global precipitation even though temperature responses are the opposite. It should also be noted that the responses vary across regions (Stjern *et al*. 2017) (section 1.3.4).

1.3.2.3 Effects on other aspects of climate

There are other mechanisms through which air pollutants influence the climate, namely through biogeochemical cycles (sections 1.4.3 and 1.4.4). For example, an increase in the O_3 concentration due to precursor emissions adversely affects vegetation, effectively reducing carbon uptake, and results in more CO_2 emissions to the atmosphere, resulting in warming (Arneth *et al*. 2010). Aerosols affect the climate through physical impacts on ocean and land biospheres and through directly depositing relevant elements in the element cycles, providing, when all combined, positive feedbacks to climate (Mahowald 2011). An example of the first type of feedback is that light-scattering aerosols can increase diffuse radiation, which enhances the biological productivity over land, thereby decreasing atmospheric CO_2 (Mercado *et al*. 2009) (Section 1.4.4).

1.3.3 Impacts on the Asian cryosphere

The glaciers and snowfields of the Hindu Kush, Karakoram, Himalayas and Tibet (HKHT) contain the largest amount of frozen water outside the polar regions. The region serves as a natural water reserve for more than 1.4 billion people living in downstream river basins (Vaux *et al*. 2012; Immerzeel *et al*. 2010; Barnett *et al*. 2005). There is growing evidence of high-altitude warming in the HKHT region, with multiple studies reporting the retreat of high mountain glaciers and early spring snow melt across the Himalaya region (IPCC 2007; Kulkarni *et al*. 2007). There are several reasons behind the increasing rate of glacial retreat in the central and western Himalayas in recent decades (Raina and Sangewar 2007; Jain 2008), including air pollutants, mainly BC and mineral dust (Bolch *et al*. 2012; Qian *et al*. 2011; Menon *et al*. 2010; Flanner *et al*. 2009).

Air pollution impacts on the cryosphere – snow, ice and frozen ground – in Asia are an important regional issue. Deposition of light-absorbing aerosols – mineral dust and BC – over the glaciers and snowfields can accelerate snow and ice melt and thus cause the retreat of mountain glaciers (Gul *et al*. 2018; Qian *et al*. 2015; Doherty *et al*. 2013; Painter *et al*. 2010). In addition, heating of the atmosphere by light-absorbing species can cause extensive enhanced warming and also contribute to accelerated melting of glaciers. This is the reason why BC is thought to play an important role in the rapid retreat of Himalayan-Tibetan Plateau glaciers (Yao *et al*. 2012). The Himalayas-Tibetan region is affected by BC emissions from South Asia, East Asia, West Asia and Europe as well as from within the region itself (Li *et al*. 2016; Lu *et al*. 2012; Babu *et al*. 2011). According to the 2012 results of Lu *et al*. (2012), BC received by the Himalayan-Tibetan Plateau increased by 41 per cent from 1996 to 2010, implying that the BC problem is accelerating in the region. South and East Asia are the main source regions, accounting for 67 per cent and 17 per cent respectively of BC transported to HKHT on an annual basis, with minor contributions from the Middle East, ~4 per cent; Europe, ~2 per cent; and Northern Africa, ~1 per cent. However, several recent studies show that the impact of internal Tibetan sources (for example, yak dung combustion by local residents) on the atmosphere of the Tibetan Plateau should not be overlooked (Zhang *et al*. 2017). Dust particles from adjacent deserts and dry areas can also play important roles in snow darkening. One study shows that the contribution of dust to snow darkening and albedo reduction on the Zhadang glacier on Mt. Nyainqentanglha in Tibet can reach up to 56 per cent, much higher than the effect of BC of 28 per cent (Qu *et al*. 2014).

This has repercussions for water resources downstream: additional discharge of water, rises in lake levels, more frequent glacial lake outburst floods (GLOFs) and risks associated with such floods, as reported by many studies (Sun *et al*. 2018; Xiao *et al*. 2008; Ye *et al*. 2008, 2007; Yao *et al*. 2007, 2004).

It is generally agreed that light-absorbing aerosols are the cause of accelerated glacier melting; however, their contributions and that of greenhouse-gas-induced warming are yet to be better quantified (Bolch *et al*. 2012). That needs a more integrated approach using Earth system high-resolution modelling and more reliable observational datasets, including satellite data.

1.3.4 Precipitation and the Asian monsoon

In addition to deteriorating air quality, the increasing trend of floods and droughts in Asian monsoon regions poses a severe threat to the 60 per cent of the world's population living in those regions as well as to the fragile ecosystems where monsoon rains are considered the main source of water for arable lands. The increasingly erratic nature of the monsoon can cause loss of lives and destruction of farmlands, damage livelihoods and property and incur extensive financial loss (Yi *et al*. 2015).

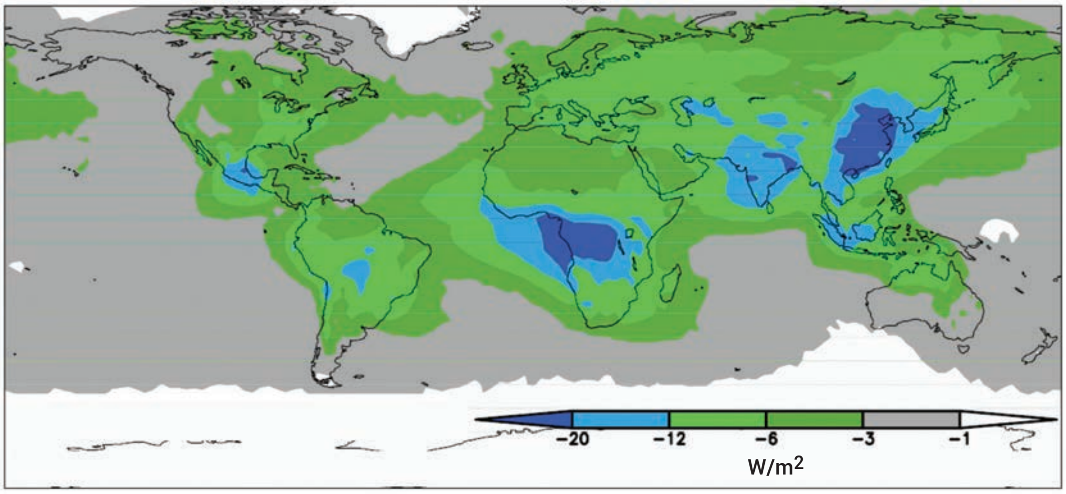
Aerosols over these monsoon regions can alter rainfall patterns (Lau and Kim 2006; Menon *et al*. 2002; Ramanathan *et al*. 2001). Weaker trends in Indian monsoon precipitation and a north-south shift in precipitation in East Asia have been observed (Cowan and Cai 2011; Menon *et al*. 2002) that have been linked to changes in the emissions of aerosols and other pollutants from within and outside Asia (Ganguly *et al*. 2012).

The Asian monsoon shows a strong spatiotemporal variability due to complex topography, diverse emission sources, aerosol types and impacts of aerosols and greenhouse gases. There are still uncertainties in estimating impacts on Asian monsoon patterns (Wu *et al*. 2012a, 2012b; Ramanathan and Feng 2009; Wu *et al*. 2007). Furthermore, global emissions from forest fires and anthropogenic activities produce a warmer stratosphere and relatively cooler troposphere (Ming *et al*. 2010) for several reasons, such as reduced convection in the lower troposphere.

BOX 1.2: REGIONAL HAZE AND DIMMING

Atmospheric aerosols lead to a major redistribution of solar forcing in the atmosphere and on the surface (Figure 1.9). In the atmosphere, light-absorbing aerosols, particularly BC and BrC, result in a large positive radiative forcing compared to surface and top-of-the-atmosphere forcings. This effect is known as atmospheric solar heating. At the surface, however, a dimming effect is observed (Figure 1.11): less sunlight reaches the surface because the aerosol mixture overhead reduces the amount of radiation reaching the Earth's surface – BC and BrC absorb incoming solar radiation while inorganic aerosols such as sulphate, nitrate and ammonium and other organic aerosols reflect it. This leads to a negative radiative forcing, a cooling, at the surface. This redistribution of heat as well as moisture is an important driver of observed changes in the Asian monsoon and the hydrological cycle (section 1.3.4.) Taken together, the summed effect of atmospheric solar heating and surface dimming gives the top-of-the-atmosphere radiative forcing, which is the relevant term for determining the effect on temperature change.

It has been estimated from simulations that South Asia's atmosphere has warmed at the rate of 0.25°C per decade since 1950 (Ramanathan *et al*. 2007). The reason behind the additional warming, besides greenhouse-induced warming, is mainly the presence of BC content in haze over the Indo-Gangetic Plains and nearby areas, including the Himalayan-Tibetan mountain regions, 2,000–5,000 metres above sea level (Ramanathan and Carmichael 2008). Several glaciers and snowfields are located at this altitude. Atmospheric heating induced by BC and its deposition on snow and ice are linked to the accelerated observed retreat of the glaciers in the region (Ramanathan *et al*. 2007) (section 1.3.3).



Note: uncertainty in the forcing is ±30 per cent.

FIGURE 1.11: SURFACE DIMMING DUE TO AEROSOLS FOR THE 2001–2003 PERIOD

Source: Ramanathan and Carmichael 2008

1.3.5 Impacts of climate change on air quality

It is not only the case that air pollution affects regional and global climate; climate change will also have an effect on and consequences for local and regional air quality and air quality management. Changes in climate affect air quality through several different mechanisms, the most relevant of which include:

1. changes in temperature that affect chemical production and loss rates, most relevant for O_3 production, and precursor emissions;
2. changes in local and regional circulation that lead to changes in dispersion; and;
3. changes in precipitation that effect changes in wet deposition of chemical species (Jacob and Winner 2009).

A strong correlation is observed between temperature and elevated O_3 concentrations in polluted areas (Otero *et al*. 2016; Jacob and Winner 2009) – the so-called 'climate penalty'. In the case of East Asia, Lee *et al*. (2015) predict increases in annual average maximum daily eight-hour O_3 of 9 parts per billion (ppb) by the end of the century compared to the 2000s under their highest emissions scenario (IPCC SRES A2). Their model study shows that for China the change in O_3 air quality is most dependent on precursor emission changes, but that for Japan, changes in O_3 air quality depend more on climate change (Lee *et al*. 2015).

Understanding how particulate matter pollution will change in a changing climate is complex and more uncertain than in the case of O_3. A global study (Horton *et al*. 2014) predicted that changes in atmospheric circulation driven by global warming will lead to increases in the occurrence of stagnation events over much of the globe, including Asia, with particularly acute impacts in India. Increased stagnation means increased human exposure to air pollution because the polluted air builds up at the surface instead of being dissipated by winds and circulation.

Changes in precipitation are also expected to have a large impact on particulate matter concentrations because wet deposition is the dominant removal mechanism of particulate matter from the atmosphere. However, regional-level changes in precipitation under climate change, due to greenhouse gases or air pollutants, or both, remain fairly uncertain, especially at the regional to local level (Hartmann *et al*. 2013).

In a recent study of the city of Beijing, Cai *et al*. (2017) predict that climate change will cause a 50 per cent increase in the frequency of weather conditions conducive to winter haze episodes. In addition, the persistence of haze-favourable weather conditions is predicted to increase. These local effects are attributed to large-scale circulation changes induced by climate change, including a weakening of the East Asian winter monsoon. This study also implies a climate penalty for air pollution in Beijing, where future climatic conditions will require even greater reductions in emissions to reach air quality goals, as would also be the case today. Better understanding of how climate change will affect particulate matter pollution on a regional to local scale in different parts of Asia will require more high-resolution and local studies.

1.3.6 The significance of short-lived climate pollutant strategies

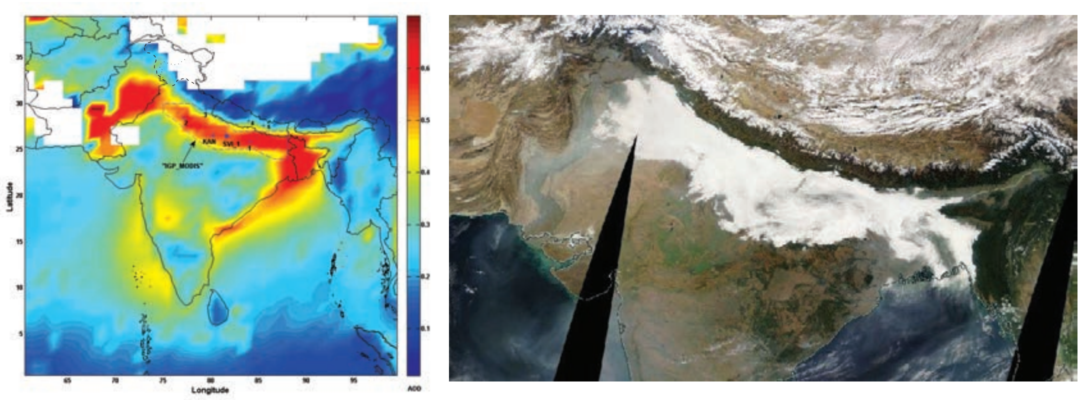
There is interest, as well as an increasing body of scientific studies, in jointly addressing air pollution and climate change in policies that promote measures that offer multiple co-benefits, especially those cutting SLCP emissions (Shindell *et al*. 2017; Maione *et al*. 2016; Akimoto *et al*. 2015; Victor *et al*. 2015; Schmale *et al*. 2014; Shindell *et al*. 2012; Williams 2012; UNEP 2011; UNEP/WMO 2011; Ramanathan and Xu 2010). These studies show that swift and wide implementation of easily available solutions would lead to climate benefits. Some studies report that half a degree of warming can be avoided by 2050 through such measures (Shindell *et al*. 2012; UNEP/WMO 2011). Others indicate that climate benefits in terms of reduced temperature may be limited (Stjern *et al*. 2017; Shoemaker *et al*. 2013). Further studies are needed, however, to fully define the climate benefits of SLCP mitigation.

In integrating the two perspectives, however, there are also trade-offs that need to be considered to make the most of potential synergies. The physical aspects of such issues are discussed here, while

BOX 1.3: VISIBILITY AND WINTER FOG IN SOUTH ASIA

Moisture and cold temperatures alone are not enough to form fog; water vapour requires the presence of particles on which to condense. Los Angeles, California saw a decrease in fog as it cleaned up its air pollution problem and ambient aerosol concentrations dropped (LaDochy 2013). Some cities in Asia have experienced the reverse: they have observed denser and more persistent fog, partly due to increases in air pollution (Syed *et al*. 2012). Central and eastern China have seen a doubling of fog frequency over the past three decades as aerosol concentrations have increased (Niu *et al*. 2010).

In the Indo-Gangetic Plain, the increase in fog appears to be associated with the rising trends of anthropogenic air pollution (Habib *et al*. 2006). In fact, the region covered with winter fog (Figure 1.12b) has also been observed to have heavy aerosol loads in the atmosphere (Figure 1.12a).



(A)

(B)

FIGURE 1.12: (A) AEROSOL OPTICAL DEPTH ACQUIRED WITH MODIS INSTRUMENT ONBOARD TERRA SATELLITE AND (B) MODIS IMAGE SHOWING CLOUDS AND FOG OVER THE INDO-GANGETIC PLAIN ON 20 NOVEMBER 2017

Source: (a) Praveen *et al*. 2012; (b) NASA

In Delhi, the fog onset was found to match times of high aerosol concentrations as well as high CO levels – a tracer of combustion (Payra and Mohan 2014; Mohan and Payra 2009). Field observation at Delhi airport in winter 2015–2016 found that the fog occurred in a highly polluted environment dominated by combustion and vehicular emissions (Ghude *et al*. 2017). During winter, aerosols over the Indo-Gangetic Plain predominantly originate from biomass burning and agricultural waste burning (Ram *et al*. 2011; Gustafsson *et al*. 2009). In Kanpur, a large fraction of measured organic aerosols were found to be from biomass burning (Sarkar *et al*. 2013). Cold ground, stable air and low wind speeds that accompany fog also trap pollutants near the ground and allow near-surface build-up of pollution (Khokhar *et al*. 2015; Sharma *et al*. 2011).

other dimensions including economics, regulatory frameworks, implementation and institutions are discussed in Chapter 3.

There are various differences between climate change and air pollution that have potential for creating trade-offs between the two sets of policies. Broadly, while air pollution measures typically concern local and regional scales on short timescales, climate measures address global impacts on long timescales. At the level of individual pollutants, the magnitudes and even the signs of climate impacts differ between components, for example BC and SO_2 (Figure 1.9). The timescales of radiative impacts span a large range: the atmospheric residence time of BC is days or weeks, for CH_4 decades, and centuries and millennia for CO_2 (Joos *et al*. 2013; Archer *et al*. 2009), leading to a variety of timescales in temperature impacts (Figure 1.9). Furthermore, uncertainties in climate effects are generally very large.

Such diversity and uncertainty pose a challenge for linking the two sets of policies. Benchmarking the climate effects of air pollutants against those of CO_2 is difficult, as evident in the decades-long debates on emission metrics, an index to equate emissions of non-CO_2 components on the common scale of CO_2 (Myhre *et al*. 2013b; Johansson 2012; Fuglestvedt *et al*. 2010; Tanaka *et al*. 2010; Shine 2009; O'Neill 2003; Manne and Richels 2001; Skodvin and Fuglestvedt 1997; Lashof and Ahuja 1990). Because of the diversity in the atmospheric characteristics of climate forcing agents, such benchmarking depends critically on the assumed basis for comparison such as the time horizon. In an attempt to resolve these issues, new thinking has recently been put forward to make use of multiple metrics in order to better capture diverse climate impacts (CCAC 2017; Ocko *et al*. 2017; Cherubini *et al*. 2016; Cherubini and Tanaka 2016; Levasseur *et al*. 2016a, 2016b). Such new approaches complement one metric representing long-term impacts with another emphasizing short-term ones.

Lastly, it needs to be remembered that global climate change is primarily caused by anthropogenic CO_2 emissions. Short-lived climate pollutant interventions focusing on BC, O_3 and HFCs contribute to slowing global warming only in short-term decadal timescales; urgent and strengthened measures for cutting CO_2 emissions are indispensable (Tanaka and O'Neill 2018) in parallel with SLCP interventions to solve global climate change (Shoemaker *et al*. 2013; Shindell *et al*. 2012; Berntsen *et al*. 2010).

1.3.7 Conclusions

- Carbon dioxide and air pollutants share many emission sources and are often emitted together from the same tailpipe or smokestack, giving potential for mitigation measures tackling air quality and climate change simultaneously to achieve multiple benefits. Other air pollutants, such as BC, CH_4, ground-level O_3 and HFCs, referred to as SLCPs, affect the climate in the short-term (decadal timescales) and offer further benefits related to human health, crop yields and climate change.

- Emissions of air pollutants and aerosol/particulate pollution precursors impact the climate at global scales and can influence precipitation, fog and haze formation and glacial melt at regional scales. There are several reasons behind the increasing rate of glacial retreat in the central and western Himalayas in recent decades, including air pollutants, mainly BC and mineral dust.

- A weaker trend in the Indian monsoon precipitation and a north-south shift in precipitation in East Asia have been observed and linked to changes in the emissions of particles and other pollutants from within and outside Asia. However, there are still uncertainties in estimating the impacts of air pollution on the Asian monsoon due to the complex topography, diverse emission sources, and a wide range of pollutants with potentially complex impacts.

- Future changes in climate are known to affect air quality by influencing the formation and removal processes of tropospheric O_3 and aerosols/particulate pollution.

- There is an increasing interest in simultaneously addressing air pollution and climate change through policies to promote measures offering multiple benefits, especially those that aim to reduce emissions of SLCPs. Policies that focus on reducing BC and ground-level O_3 in the atmosphere contribute to slowing global warming and reducing air pollution. These policies should, however, complement and not replace those reducing CO_2.

- The links between air quality and climate change are complex and an active area of scientific research. Understanding the interplay between air quality and climate change is key for integrated policy making that can maximize air quality and climate benefits.

1.4 AIR QUALITY, AGRICULTURE AND ECOSYSTEMS

1.4.1 Introduction

This section considers the evidence of impacts of air pollution on agriculture and ecosystems in Asia and the Pacific. It focuses on the major air pollutants of concern: tropospheric O_3, also known as ground-level O_3 (section 1.4.2); acidic and eutrophying deposition (section 1.4.3); and particulate matter (section 1.4.4) through a compilation of evidence from global and Asian studies. The impacts of air pollution on the carbon cycle are also considered (section 1.4.5).

Although not all the impacts reported in this section will occur over the entire Asia and Pacific region, areas with similar pollution levels and crop and ecosystem sensitivity are likely to experience them. The section outlines the strength of the evidence base underpinning the modelling of crop-yield loss due to tropospheric O_3 in Chapter 2, and also assesses evidence of other benefits for crops and ecosystems, as well as possible trade-offs, when action is taken to reduce air pollution.

Tropospheric O_3 is widely recognized as the most damaging air pollutant to vegetation due to its phytotoxicity and prevalence at high concentrations over rural/agricultural regions, often located downwind of emission sources (Ainsworth *et al*. 2012; Royal Society 2008). Exposure to relatively low levels of tropospheric O_3 – less than 40 ppb – are known to have negative effects on crop productivity and natural ecosystems (Ainsworth 2016; Emberson *et al*. 2009).

Concentrations of tropospheric O_3 have been observed to follow increasing trends in both large urban areas and their surroundings in Asian developing countries (Wang *et al*. 2016; Ainsworth *et al*. 2012; Nghiem and Kim Oanh 2009; Royal Society 2008). Limited monitoring data on suburban and rural O_3 concentrations in Asia also indicate that monthly mean O_3 concentrations now commonly reach 50 ppb during important agricultural growing seasons (EANET 2016). Four-week mean O_3 concentrations, measured using passive samplers, in the major agricultural regions of Pakistan have been found to exceed 45 ppb (Ahmad *et al*. 2013). Ozone monitoring in the Indo-Gangetic plain of India reported daytime 12-hourly mean monthly O_3 tropospheric concentrations varying from 45–62 ppb during summer to 24–44 ppb during winter and rainy months (Mishra and Agrawal 2015; Chaudhary *et al*. 2013; Tiwari *et al*. 2008). Modelling studies at the regional and global scale (Ghude *et al*. 2014; Dentener *et al*. 2006) project that under current legislation emission scenarios, parts of Asia will experience further significant increases in tropospheric O_3 concentrations by 2030. The implications of these conditions for impacts to crops and vegetation in the region are considered in section 1.4.2.

Other pollutants also have adverse impacts on crops and ecosystems. Particulate matter and its precursors, including those that are transported over large distances – sulphate, nitrate and ammonium particles – can cause adverse effects on ecosystems and their biodiversity, for example through excessive nutrient enrichment of ecosystems and acidification, which can affect crop production and important ecosystem services (Duan *et al*. 2016; EEA 2014; Jones *et al*. 2014; Hicks *et al*. 2008). Important ecosystem services include provisioning food, fibre, timber and medicines; regulating freshwater flows, preventing erosion and providing protection from extreme climate events; supporting oxygen production and nutrient cycles; and providing opportunities for recreation and tourism. The effect of air pollutants on ecosystems is particularly problematic for Asia due to a number of factors that combine to enhance the likelihood of damage (section 1.4.3).

Atmospheric aerosol or particulate matter including BC can alter the amount of solar radiation reaching the Earth's surface – known as global dimming – and can also influence atmospheric and surface warming through reflection/scattering and albedo processes, respectively (section 1.3). These effects can disturb photosynthesis, which is dependent upon photosynthetically active radiation and temperature, and in turn influence plant growth and productivity (Burney and Ramanathan 2014). High levels of particulate matter have been reported in the Asia and Pacific region (Hopke *et al*. 2008; Kim Oanh *et al*. 2006) that are well above those in developed countries around the world; hence the effects of particulate matter on ecosystems may be substantial. Section 1.4.4 shows how particulate matter effects on solar radiation can have both positive and negative impacts on vegetation and that further studies in the region are required to determine the true nature of the impact.

It is also worth noting that plants appear to be even more sensitive to a number of air pollutants, such as nitrogen dioxide (NO_2), O_3 and SO_2, than humans; hence even if compliance with the WHO Guideline for protection of human health is achieved as suggested in this report, problems for crops and ecosystems may remain (Bell *et al*. 2011).

1.4.2 Ozone impacts on important crops and ecosystems

1.4.2.1 Evidence of ozone impacts on crops and ecosystems

Ozone is a strong oxidizing gas; once it enters a plant through the stomata it causes damage through oxidative processes (Heath 2008) similar to the oxidative stress caused by high and low light intensities, drought and cold stress. The result is that exposure to O_3 can cause damage to foliage and reduce pigment content in leaves, which affects plant growth and yield (Tomer *et al*. 2015; Agrawal *et al*. 2003); this can occur with or without visible symptoms of injury.

Visible injuries due to O_3 show as flecking and bronzing of the upper leaf surface (Figure 1.13). Other consequences of O_3 damage include reductions in photosynthesis, alterations in carbon allocation and reduction in yield quantity and quality (Feng *et al*. 2015; Fuhrer 2009). Ozone can also affect forest (Sicard *et al*. 2016) and grassland productivity (Wei *et al*. 2007), but not many studies have been conducted for these ecosystems in Asia (Feng *et al*. 2014).

Effects of ground level O_3 on crops were first observed in North America and later in Europe (Fuhrer and Booker 2003) and these catalysed more concerted efforts to conduct research to quantify impacts. When considering yield effects alone, a seminal paper by Mills *et al*. (2007) gives a good indication of the relative sensitivities of a number of different crop species. This and other review papers, however, tend to include only very few Asian studies since, until recently, empirical data for the Asian region have been rather limited and only collected by a few research groups.

The magnitude of response to O_3 varies significantly not only between crops – beans, for example, are more sensitive than maize or rice (Mills *et al*. 2007) – but also amongst cultivars of the same crop. For example, Japanese rice cultivars may be less sensitive to O_3 than other cultivars used in experiments (Yonekura and Izuta 2017). Emberson *et al*. (2009) suggested that the Asian-grown wheat and rice cultivars may be more sensitive to O_3 than their North American counterparts. Likewise, Sinha *et al*. (2015) suggested that the Indian rice and wheat cultivars appeared to be more sensitive to O_3 than are their European and Southeast Asian counterparts.

It is important to note that the climate regime and management practices that vary globally are also likely to influence crop and, potentially, forest sensitivity to O_3 (Luo *et al*. 2013; Chen *et al*. 2011). In recent years, an increasing number of experimental and modelling studies have been conducted for crops grown in Asia (Gudhe *et al*. 2014; Tai *et al*. 2014; Emberson *et al*. 2009; Wang and Mauzerall 2004) that have increased knowledge of the response to O_3 of Asian crop species.

A wide range of experimental methods have been used to assess O_3 damage to plants, including field observation of injury and damage; biomonitoring studies using O_3 protectants such as anti-oxidant chemicals – for example, ethylene diurea (EDU) – (Shamsi 2007; Agrawal *et al*. 2005), or using O_3-sensitive versus resistant plants; controlled fumigation and filtration studies using open-top chambers (OTCs) (Wahid *et al*. 1995); and free air concentration enrichment (FACE) studies (Kobayashi 2015).

These experimental studies have been conducted in different parts of the world over the past 40 years, starting in North America (Heck *et al*. 1988) and later Europe (Jäger *et al*. 1992). In Asia, studies have been conducted since the 2000s in Japan and other East Asian countries (Jin *et al*. 2001; Kobayashi *et al*. 1995) and have focused on several types of regionally important crops, including peanuts, rice and wheat (Van and Kim Oanh 2009; Van *et al*. 2009; Shamsi, 2007; Ishii *et al*. 2004; Wahid *et al*. 1995). A summary of the experimental study results showing yield reductions and changes in biomass of major Asian crops is given in Table 1.1.

Research is now starting to focus on developing a better understanding of the mechanisms of O_3 damage, both in relation to stomatal O_3 uptake and the consequent impacts on photosynthesis growth, senescence and yield loss (Emberson *et al*. 2018). An important aspect of this impact mechanism is whether the main damage caused

a) Rice (*Oryza sativa*) b) Maize (*Zea mays*) c) Onion (*Allium cepa*)

d) Peanut (*Arachis hypogaea*) e) Soybean (*Glycine max*) f) Wheat (*Triticum aestivum*)

Note: Typical injuries caused by O_3 include the appearance of yellow or dark brown stipples or flecks and bronzing in the interveinal region of leaves. These symptoms emerge due to chlorophyll bleaching that causes yellowing in leaves (chlorosis) and localized death of leaf tissues (necrosis), which can expand to larger areas depending on the exposure and sensitivity of the plant.

FIGURE 1.13: SOME TYPICAL O_3 INJURIES: A) BRONZING ON LEAVES OF RICE (*ORYZA SATIVA*); B) INTERVEINAL CHLOROSIS IN LEAVES OF MAIZE (*ZEA MAYS*); C) INTERVEINAL CHLOROSIS IN ONION LEAVES (*ALLIUM CEPA*); D) INTERVEINAL CHLOROSIS (WHITE PATCHES) AND NECROSIS (BROWN PATCHES) IN LEAVES OF PEANUT (*ARACHIS HYPOGAEA*) ALONG WITH SMALLER PLANT BIOMASS; E) BRONZING ON THE LEAF SURFACE OF SOYBEAN (*GLYCINE MAX*) AND F) INTERVEINAL CHLOROSIS IN LEAVES OF WHEAT (*TRITICUM AESTIVUM*)

Photos: CEH: rice, maize, onion and soybean; Van and Kim Oanh: peanut; and A. Mishra, Banaras Hindu University: wheat.

TABLE 1.1: YIELD REDUCTIONS IN MAJOR CROPS IN ASIA AT ELEVATED OZONE CONCENTRATIONS IN EXPERIMENTAL STUDIES

Crops	**Yield reductions (%) and O_3 exposure levels (ppb)**		
	India/South Asia	**China/East Asia**	**Southeast Asia**
Maize	7.2–13.8% (+15 and +30 ppb)		
Mung bean	9.8–15.4% (+10 ppb)		
Peanut			27–49% (32–113 ppb)
Rice	34–38% (35 ppb)	8.2–43% (60–200 ppb)	10–48% (32–113 ppb)
Soybean	12–20% (+10 ppb)		
Wheat	11.6–65.6% (60–100 ppb)	8.5–73% (70–200 ppb)	

Note: These are mostly OTC studies; (+) indicates the elevated dose above ambient levels. See Annex 1.2 for more details.

by O_3 is instantaneous, on the photosynthetic system, or more long-term through, for example, earlier and accelerated senescence. Understanding these mechanisms is important since it would allow more dynamic modelling than has been performed to date. This would also allow opportunities to consider how O_3 effects may be influenced by other plant stresses, for example those resulting from climate change, elevated CO_2, soil nutrient stress or soil water stress.

In addition to the quantitative reduction in crop yield, ambient and elevated O_3 can affect the quality of crops (Rai *et al*. 2016). Yields of leafy crops are notably decreased due to visible damage to the leaves, thus reducing the crops' economic value (Ainsworth 2016). With respect to the quality of grain crops, elevated O_3 decreases starch, protein and nutrient contents in wheat and rice grains (Box 1.4) (Rai *et al*. 2010; Rai *et al*. 2007).

Effects of O_3 on Asian tree species have also been studied intensively in Japan and China, and most of these studies have been summarized in a book edited by Izuta (2017). Many of these filtration studies, in which comparisons are made between plants grown in clean, filtered air and those grown in ambient air, suggest a significant reduction of tree biomass caused by the current level of O_3 concentrations in East Asia, where a 10 per cent reduction in whole plant dry mass was observed for O_3-sensitive trees at exposures above 40 parts per million over the growing season of six months (Kohno *et al*. 2005).

Reduction of biomass in tree species can directly influence the annual carbon cycle. The O_3-induced reduction in the total annual carbon absorption/assimilation of three conifer tree species in Japan was estimated to be 0.8 per cent (Watanabe *et al*. 2010). In Beijing, China, visible injuries due to O_3 were observed (Feng *et al*. 2014) as field evidence of O_3 pollution for 28 species of crops, native plants and ornamental plants. These observations were found to be more frequent in rural areas and mountainous regions downwind from the city, and less frequent in city gardens. The O_3 monitoring data from remote areas including mountains and

BOX 1.4: EFFECTS OF GROUND-LEVEL OZONE ON WHEAT AND RICE

The OTC experiment results from Zheng *et al*. (2013) revealed an increase in a range of key nutrients including calcium (Ca), copper (Cu), nitrogen (N), potassium (K), sulphur (S) and zinc (Zn) in rice exposed to O_3. The concentrations of protein and amino acids such as lysine ($C_6H_{14}N_2O_2$) in winter wheat and rice were also increased, while the concentration of amylose ($(C_6H_{10}O_5)n$) decreased. However, because of the more significant reduction of the grain yield in both winter wheat and rice, the absolute total amount of nutrients produced in the crop was reduced by elevated O_3 (Zheng *et al*. 2013). For rice, elevated O_3 significantly increased grain chalkiness and the concentrations of essential nutrients, which was particularly significant for Zn and Cu.The O_3-induced changes in starch pasting properties, for example a decrease in $(C_6H_{10}O_5)n$ concentration, indicated a deterioration in the cooking and eating quality (Wang *et al*. 2014). The contents of protein, total amino acids (TAA), total essential (TEAA) and non-essential amino acids (TNEAA) in rice grain increased with elevated O_3 concentration (Zhou *et al*. 2015; Wang *et al*. 2014). A similar significant response to O_3 was observed for concentrations of the seven essential and eight non-essential amino acids. In contrast, elevated O_3 caused a small but significant decrease in the percentage of TEAA within TAA (Zhou *et al*. 2015).

large expanses of forests are, however, still limited and this has so far prevented comprehensive studies of O_3 effects on forests.

In many Asian countries, a lack of monitoring data describing O_3 concentrations, especially in rural and remote areas, is the first obstacle to a comprehensive assessment of the impact of O_3 on crop yield losses. Regional-scale risk assessments of O_3 damage therefore rely mostly on modelling methods that use estimates of O_3 concentration derived from global or regional atmospheric chemistry transport models (CTMs). These concentration fields can then be combined with data describing crop distribution and production along with empirically derived statistical relationships between crop yield and O_3 concentration to estimate crop production losses. Several concentration-response metrics (AOT40, M7/M12 and W126, for example) have been used to quantify crop yield loss due to O_3 concentrations (Danh *et al*. 2016; Gudhe *et al*. 2014; Avnery *et al*. 2011; van Dingenen *et al*. 2009; Wang and Mauzerall 2004; Aunan *et al*. 2000). Based on simulated O_3 levels, the rice yield loss in Thailand was estimated at 0.84 per cent for the second crop growing in high O_3 months, November–April in 2003–2004 with the maximum loss of 2.6 per cent occurring in provinces surrounding Bangkok (Nghiem 2007).

More recently, flux-response metrics have been developed that account for the influence of environmental conditions limiting stomatal O_3 uptake. Tang *et al*. (2013) used such a metric, derived from experiments conducted at a FACE site in China, and found relative yield losses for wheat for the whole of China to be in the range of 6.4–14.9 per cent. Danh *et al*. (2016) used the flux-response approach and estimated the rice yield loss in the southeastern part of Viet Nam in 2010 to be in the range of 0.51–5.7 per cent, varying with crop cycle. Other approaches include the development and application of statistical regression models that can relate pollutant concentrations to actual yields that occur over a number of years across different regions. Burney and Ramanathan (2014) derived such a statistical regression model from relationships between yield from 1980–2010 with O_3 and BC pollution estimated from emission data. They showed that the yield loss of wheat due to these pollutants was 18.9 per cent for the whole of India in 2010. Table 1.2 presents the range of crop yield losses estimated using AOT40 and M7 metrics based on a recent review by Ainsworth. (2016) and several other studies for rice crops.

TABLE 1.2: ESTIMATED YIELD LOSSES USING MODELLING STUDIES

	World %	North America %	European Union %	China/East Asia %	India/South Asia, Southeast Asia %
Maize					
AOT40	2.2–2.4	2.0–2.2	3.1–3.5	3.8–4.7	2.0–3.4%
M7	4.1–5.5	3.6	5.1–7.9	7.1–8.0	4.0–8.0%
Rice					
AOT40					1.6–4.0[a], 2.1[e]
M7				1.1–1.5[c], 3–5[d]	0.35–0.45[a], 0.84[b]
Soybean					
AOT40	5.4–8.5	7.1–12.0	20.5–23.9	11.4–20.9	3.1–4.7, 2.7[e]
M7	13.9–15.6	16.9–17.7	27.3–27.4	20.8–24.7	13.2–19.1
Wheat					
AOT40	12.3–15.4	4.1–11.0	4.1–12.1	16.3–19.0	26.7–27.6, 5[e]
M7	3.9–7.3	2.6–4.4	3.3–4.6	3.3–9.8	8.2–13.2

Note: [a] Danh *et al*. 2016 (southeastern part of Vietnam); [b] Nghiem 2007 (Thailand); [c] Aunan *et al*. 2000 (China); [d] Wang *et al*. 2014 (China); [e] Ghude *et al*. 2014 (India). Other data are based on Ainsworth (2016).

Modelling studies have also been conducted to investigate the impact of future projected O_3 concentrations on crops in Asia. Increases in the future emissions of O_3 precursors in China would lead to increases in surface O_3 which could cause substantial reductions in crop production in the country (Aunan *et al*. 2000). Given projected increases in O_3 concentrations in East Asia, it is estimated that grain yield loss would increase by 2–16 per cent for maize, rice and wheat, and 28–35 per cent for soybeans in 2020 compared to 1990 (Wang and Mauzerall 2004).

1.4.2.2 Factors affecting the extent of ozone impacts

High concentrations of tropospheric O_3 during crop growing seasons lead to substantial reductions in the yields of different crops (Rai *et al*. 2016). A study focused on Punjab and Haryana, India's major agricultural regions, indicated yield losses due to O_3 in the range of 27–41 per cent for wheat, 21–26 per cent for rice and 3–5 per cent for maize in 2012–2014 (Sinha *et al*. 2015). Such studies show that higher yield losses can occur in heavily polluted regions for sensitive varieties, especially when they also suffer from such additional stresses as rising temperatures during the growing season. The timing of the crop growing season can also be important. There are, for example, two or three rice crop cycles a year in many parts of Southeast Asia, and the crops grown in the months with high O_3 levels are most susceptible to both current and future increasing O_3 levels in countries such as Thailand (Nghiem 2007) and Viet Nam

(Danh *et al*. 2016). Lal *et al*. (2017) modelled estimates for the losses of wheat and rice yields using surface O_3 observations from a group of 17 sites, for the first time, covering different parts of India, which showed a total all-India annual loss of 4.0–14.2 million tonnes, 4.2–15.0 per cent of the total wheat crop, and 0.3–6.7 million tonnes of rice, 0.3–6.3 per cent of the total crop. The lower losses of rice were mainly due to lower surface O_3 levels during the cropping season after the Indian summer monsoon.

The sensitivity of plants to changes in O_3 concentrations due to climate conditions makes the projection of the effects of air pollution on plants in future climate change scenarios complex. Drought stress and increasing temperatures, for example, will reduce stomatal conductance and therefore the uptake of O_3 to the internal cellular sites where damage occurs. The limited number of studies that have been carried out on crops to explore drought-O_3 interactions (Feng and Kobayashi 2009) have found that the direct damaging effect of drought stress on yield often outweighs the positive impact of O_3 exclusion (Fangmeier *et al*. 1994).

The CO_2 fertilization effect is also considered likely to result in less O_3 damage since the stomates, the leaf pores that allow gas exchange, will tend to close to conserve water whilst allowing the same levels of CO_2 uptake for photosynthesis (Feng *et al*. 2009). Similar responses will likely occur in forest ecosystems (Fleisher *et al*. 2005). Beside the interactions between climate variables and O_3 uptake, a plant already stressed by, for example, drought or heat, may be more sensitive to an internal O_3 dose. To fully understand these interactions further empirical research is required.

Asia is the world's most populous continent with large emissions from key economic sectors (Chapter 2). High emissions of O_3 precursors (Figure 2, Introduction) coupled with favourable meteorological conditions (Permadi and Kim Oanh 2008; Zhang and Kim Oanh 2002) enhance tropospheric O_3 formation and build-up. The mixed land-use pattern commonly observed in Asian developing countries with agricultural land adjacent to urban areas increases the exposure of agricultural crops to air pollutants of urban origin, especially to O_3 that is normally found at higher concentrations downwind of large urban centres (Nghiem and Kim Oanh 2009). The declines in crop yield due to air pollution, and O_3 in particular, result in the need for additional cropland to meet food demand and hence cause further land-use change. Chuwah *et al*. (2015) estimated that for 2005, the crop production losses for maize and rice in Asia were up to 5 tonnes per square kilometre (km^2) in some parts of China and India. If air pollution policies are not strengthened, crop production losses in 2050 might go up to 10 tonnes/km^2. The study further projected that if air pollution mitigation were not implemented, crop losses due to O_3 would require that to meet demand in 2050, the global crop area would need to be increased by 2.5 per cent, approximately 1.3 million km^2. This translates into an 8.9 per cent increase in requirements for crop areas across Asia, which will put additional pressure on already scarce land resources.

1.4.3 Acidification and eutrophication effects of air pollution at local and regional scales

Air pollutants containing N and S can have a variety of effects related to acidification and eutrophication of the environment. Depending on proximity to emission sources, sensitive ecosystems and water catchments can receive a mixture of wet and dry depositions of S and reduced and oxidized N compounds. For example, dry deposition close to point sources of SO_2 emissions near power stations and NH_3 depositions near intensive animal-rearing facilities can cause local impacts. Wet depositions containing sulphate, nitrate and ammonium can cause acidification and eutrophication impacts at a regional scale.

Asia is now the global hotspot of N and S depositions (Figure 1.14); since the early 2000s, the global maximum depositions of both N and S are found in East Asia, including regions in eastern China and the Republic of Korea, Bangladesh, India, Japan, the Democratic People's Republic of Korea, Laos, Myanmar, Thailand and parts of Pakistan (Vet *et al*. 2014).

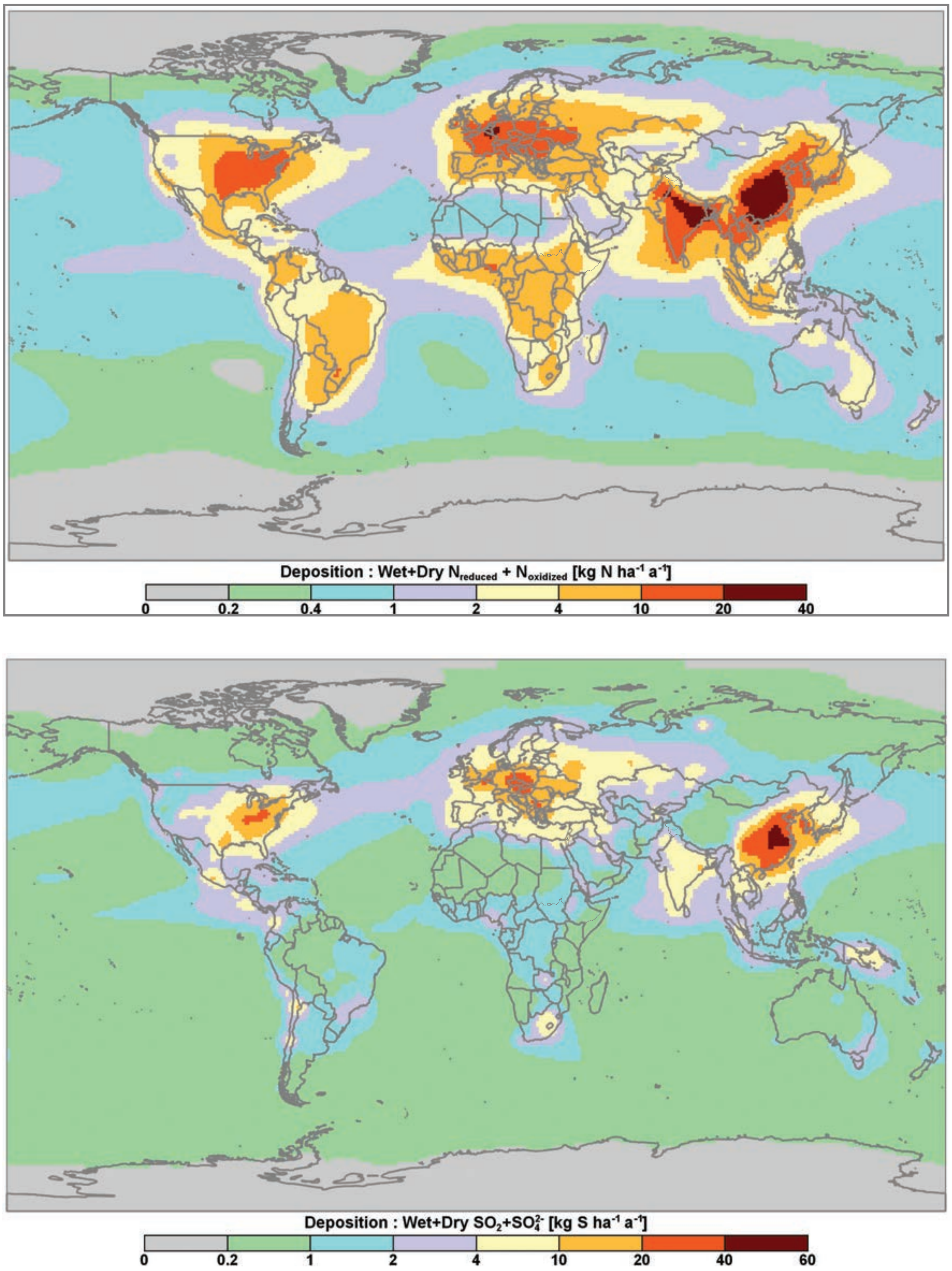


FIGURE 1.14: 2001 ENSEMBLE-MEAN PATTERNS OF NITROGEN WET AND DRY DEPOSITION OF OXIDIZED (E.G. NITRATES AND NO_X) AND REDUCED (E.G. AMMONIUM AND AMMONIA) FORMS (ABOVE) AND SULPHUR WET AND DRY DEPOSITION (E.G. SULPHATE AND SULPHUR DIOXIDE) (BELOW)

Source: Vet *et al*. 2014

Acid deposition can have both direct and indirect effects on ecosystems. The damage to crops is often regarded as the most direct impact caused by low-pH (acidity) precipitation and/or high concentrations of ambient SO_2 or NH_3. Evidence from research in China has shown that such crops as barley, spinach and wheat are susceptible to visible damage from acidic rainfall at pH 3 and a range of crops show yield losses at pH 4–5, whereas crops such as rice and peanut only show yield loss at rainfall pH of less than 2.8 (Zhang *et al*. 1998). Since the 1980s, forest decline has been observed in east and southwest China, mainly caused by direct damage on leaves due to SO_2 in the air and acidic precipitation (Ma 1991; Yu *et al*. 1990). Although direct above-ground phytotoxicity of SO_2 and acid precipitation on leaves and needles may contribute to the death of trees, the indirect effects of soil acidification resulting in aluminium (Al) activation and nutrient deficiency in the soil may be the most important long-term cause of forest decline. A recent review of the current state of knowledge regarding acid deposition and its environmental effects across Asia (Duan *et al*. 2016) shows that the characteristics of soil and surface water acidification in Asia are different from those experienced earlier in Europe and North America. The net and potential acidity of rain water are affected by other factors including the abundance of atmospheric dust rich in calcium carbonate ($CaCO_3$) in India which has been reported to increase the pH of rain water (Kulshrestha 2013).

Nitrogen deposition can have beneficial effects on crop and forestry yields as a free source of fertilizer and can also act as a carbon sink in temperate and tropical forests in Asia, with phosphorus (P) deposition being important in determining how much N deposition can stimulate growth (Wang *et al*. 2017; Du *et al*. 2016). Although N deposition can improve soil N availability and result in increased photosynthetic capacity and stimulation of plant growth in N-limited ecosystems (Bai *et al*. 2010; Xia *et al*. 2009; Fan *et al*. 2007), excess N input can also lead to restricted plant growth or even damage to plants through changes in soil N status (Fang *et al*. 2009; Lu *et al*. 2009; Xu *et al*. 2009), nutrient imbalance (Yang *et al*. 2009) or a reduction in net photosynthesis (Guo *et al*. 2014; Mo *et al*. 2008b). Examination of six forests in southern China and Japan indicated that, in addition to leaching, denitrification losses of NO_3 grew significantly with increasing N deposition, which in turn increased soil N_2O emissions (Fang *et al*. 2015). Nitrogen emissions to the atmosphere can also be exacerbated by the use of organic and inorganic fertilizers and can lead to problems of nitrate leaching and the contamination of ground and surface waters in Asia, as has occurred in China (Gao *et al*. 2016b), India (Abrol *et al*. 2017) and Japan (Nakahara *et al*. 2010). Riverine and atmospheric N inputs also give rise to toxic algal blooms in Asia (Abrol *et al*. 2017; Tian *et al*. 2017). Biodiversity could also be significantly affected by N deposition, with the level depending on soil N status, vegetation composition, dose and duration of N addition, and the N requirements of different species (Bai *et al*. 2010; Bobbink *et al*. 2010). Excessive N deposition normally reduces biodiversity, including forest understory species (Lu *et al*. 2011, 2010, 2008), grasses and forbs (Bai *et al*. 2010) and soil fauna (Xu *et al*. 2006).

1.4.4 Impacts of particulate matter on plants and ecosystems

1.4.4.1 Effects of particulate matter on radiation

Particulate matter and atmospheric aerosols have effects on solar radiation that can have both positive and negative impacts on vegetation. On the positive side, anthropogenic aerosols in the atmosphere have been associated with an increase in the diffuse fraction of incoming solar radiation that may have a positive effect on crop photosynthesis and yield (Wild 2012; Steiner *et al*. 2005). Early studies suggested that an increase in diffuse light may increase photosynthesis, because diffuse light is more able to penetrate the canopy and can promote overall total canopy photosynthesis (Gu *et al*. 2002). This may help to alleviate climate change as the carbon sequestered in plant biomass is increased, altering the global carbon cycle. Mercado *et al*. (2009) estimated that variations in diffuse fraction, associated largely with global dimming, enhanced the land carbon sink by approximately one quarter between 1960 and 1999.

On the negative side, the amount of radiation reaching the Earth's surface is an important driver of ecosystem and agricultural productivity and affects light-limited photosynthesis and both surface air and leaf temperatures. The composition of the atmosphere can reduce incoming radiation through the presence of aerosols and clouds (Cheng *et al*. 2015; Gu *et al*. 2003; Roderick *et al*. 2001); this is known as the dimming effect. This change in solar radiation has the potential to reduce CO_2 uptake in both natural vegetation and agricultural systems, as well as alter the balance of sensible and latent heat in the Earth's energy balance (Mercado *et al*. 2009; Ramanathan 2006).

Depending on the amount of scattering or extinction by clouds and aerosols, this simultaneous decrease in total radiation and increase in diffuse radiation may lead to a trade-off between the efficiency and magnitude of radiation available for photosynthesis (Oliphant *et al*. 2011; Mercado *et al*. 2009). Tie *et al*. (2016) estimated the reduction in yields in several regions of China caused by the reduction in radiation alone to be 2 per cent for the total rice crop and 8 per cent for wheat. When, however, the increase in diffuse radiation was considered, the yield reductions were lower, at 1 per cent and 4.5 per cent respectively.

Ground-based observational studies have also quantified the response of ecosystems to diffuse light. Several showed that carbon uptake would rise with the increase in atmospheric aerosol load which provided more diffuse radiation (Min 2005; Gu *et al*. 2003, 2002). Several of these ground-based studies suggest that there is a limitation to this response; for example, Knohl and Baldocchi (2008) show that photosynthesis and transpiration increase with increasing light up to a diffuse fraction of 0.45, after which the net benefit of diffuse light decreases due to the overall reduction in light levels. A comprehensive review of this topic is provided in Kanniah *et al*. (2012), and the magnitude of this effect has been tested using ground-based data sets and atmospheric models, but further studies are required under the different conditions found across the Asia and Pacific region.

1.4.4.2 Possible effects of particulate deposition to plants

High levels of total suspended particles are commonly observed in Asian developing countries. These large particles can easily deposit on trees and crops, and can subsequently alter leaf surface conditions, such as degradation/erosion of leaf-surface (epicuticular) wax and stomata occluded with particles. Stomata occluded by particulate matter have been observed on European tree species (Crossley and Fowler 1986; Grill and Golob 1983; Smith 1977) and also for Japanese cedar (Cryptomeria japonica) (Takamatsu *et al*. 2001; Sase *et al*. 1998). Accelerated water loss due to the malfunction of stomata and dry meteorological conditions in urban areas appeared to be a significant factor causing the decline of Japanese cedar trees observed in Kanto Plain near Tokyo, Japan (Takamatsu *et al*. 2001; Sase *et al*. 1998). Moreover, deposition of dark coloured particulate matter, such as BC, caused a reduction of the photosynthetic rate in crops due to a shading effect (Hirano *et al*. 1995). Izuta *et al*. (2014), using the short-term exposure test, reported that the net photosynthetic rates in Japanese tree species were reduced by 10 per cent due to relatively large amounts, 3.2–39.0 milligrams per square metre (mg/m2), of BC deposition to the leaves. In Japan, according to field observational studies in Hokkaido (Fukazawa *et al*. 2012) and Tokyo (Hara *et al*. 2014), the amounts of BC deposited on leaf surfaces were 9–14 mg/m^2 for larch and 10–15 mg/m^2 for oak, which could induce a 10 per cent reduction in the net photosynthetic rate.

Although the relevant studies are relatively limited, reduction of crop yields due to particulate matter deposition has also been suggested in the Yangtze delta region of China (Bergin *et al*. 2001). Plant leaves along big dusty roads in developing Asia are often covered with blackish dust that would occlude stomata and affect plant growth. Acidic components, sulphate and nitrate, and other components of the deposit dust can directly damage the leaves (Mishra and Kulshrestha 2017; Gupta *et al*. 2016). Therefore, the particulate matter deposition to terrestrial ecosystems should not be neglected as a possible stressor in Asia and the Pacific. Further studies are required to determine the magnitude of the effects.

1.4.5 Impacts of air pollution on the carbon cycle

There is still only a limited number of regional studies on the impacts of air pollutants on the carbon cycle. These impacts have been assessed by several mechanisms (UNEP/WMO 2011) by which air pollutants affect plant photosynthesis rates and thus CO_2 uptake. As previously described, O_3 damage to plants, aerosol dimming and acid deposition on plants and soils can affect the carbon cycle. Tropospheric O_3 can damage plants and reduce primary productivity while the increase in CO_2 concentrations is thought to stimulate plant primary productivity, referred to as the CO_2 fertilization effect. The interactive effects of O_3 and atmospheric CO_2 on plants have received much attention, although understanding is far from complete.

Sanderson *et al.* (2007) simulated the impact of increasing levels of CO_2 on stomatal conductance and surface O_3 levels using a global general circulation model. They showed that a doubled level of CO_2 would increase surface O_3 levels by 2–8 ppb in all four seasons as increased CO_2 reduces stomatal conductance, which subsequently decreases O_3 flux into plants (Ainsworth and Rogers 2007). Reduced stomatal conductance that occurs in response to elevated CO_2 may enhance plant water-use efficiency, which could help to partly alleviate the effects of reduced rainfall. Increased water stress in a warmer climate may also decrease sensitivity to O_3 through reduced uptake. These potential feedbacks are complicated in combination with the increased temperature, drought and plant transpiration that affect the water balance (Ainsworth *et al.* 2012).

When O_3 concentrations are high enough to reduce photosynthesis, less CO_2 is absorbed by the leaves of vegetation (Mills *et al.* 2013), which in turn facilitates the accumulation of CO_2 in the atmosphere. Sitch *et al.* (2007) used a global land carbon-cycle model to quantify the impact of future O_3 levels on the land carbon sink and found a significant suppression because an increase in O_3 concentrations reduces plant productivity. Watanabe *et al.* (2010) assessed the risk of O_3 reducing C absorption by tree species in Japan. Taking account of spatial distribution of accumulated O_3 exposure above a threshold of 60 ppb (AOT60), habitats of the Japanese cedar *(Cryptomeria japonica)*, Japanese pine *(Pinus densiflora)* and Japanese larch *(Larix kaempferi)* and their annual carbon absorption and sensitivities to O_3 exposure, the O_3-induced reduction in the annual C absorption in Japan was estimated and mapped. The results showed that the total O_3-induced reduction of annual C absorption by three species was 0.8 per cent.

1.4.6 Conclusions

Measures to improve air quality will have multiple benefits for the adverse effects on crop yields and ecosystem services as detailed in this section.

- Ozone, particulate matter and related pollutants, including those involved in long-range transport (SO_2, NO_x, NH_3, CH_4 and CO), can directly or indirectly affect ecosystems adversely in Asia and the Pacific, which can influence crop production and important ecosystem services.

- Recent estimates from experimental studies in Asia for important crops, such as maize, mung bean, peanut, rice, soybean and wheat, show crop-yield losses due to exposure to ground-level O_3 at the common levels found in the region that can range from 5 per cent to more than 30 per cent depending on the crop and ambient conditions – taking O_3 exposure of 50 ppb as the reference.

- Particulate matter and its precursors, including secondary particulate matter that can be transported over large distances – sulphate, nitrate and ammonium particles – can have adverse effects on ecosystems and their biodiversity in Asia, causing, for example, eutrophication and acidification that can affect crop production and damage surface water, soil quality and biodiversity.

- The influence of atmospheric aerosols or particulate matter, including BC particles, on the quality of sunlight reaching vegetation can have positive and negative impacts on plant growth and productivity. Particles deposited on trees and crops can alter leaf surface conditions and block stomata, affecting the plant growth. Further study is required to determine the net impacts of these effects and also of air pollution on the carbon cycle.

- While more research will help to quantify effects, action is justified and urgently needed to reduce O_3 concentrations and the deposition of substances causing acidification and eutrophication.

- Global photochemical models project that parts of the region will experience further significant increases in O_3 concentrations by 2030. High emissions of substances that contribute to the formation of O_3 coupled with favourable meteorological conditions enhance O_3 formation. The mixed land-use pattern commonly observed in developing countries in Asia and the Pacific, where agricultural land is adjacent to urban areas, increases the exposure of crops to O_3.

1.5 SOCIO-ECONOMIC DEVELOPMENT PATHWAYS, AIR QUALITY AND SUSTAINABLE DEVELOPMENT GOALS IN THE ASIA AND THE PACIFIC

1.5.1. Socio-economic development pathways and air quality in Asia and the Pacific

Fossil fuels have provided people with convenience and mobility for several generations, but they have also created serious environmental problems in their production and consumption processes through the emission of air pollutants as well as greenhouse gases. Air pollution resulting from fossil fuel consumption has induced adverse effects on ecosystems, the ambient environment and public health as described in previous sections.

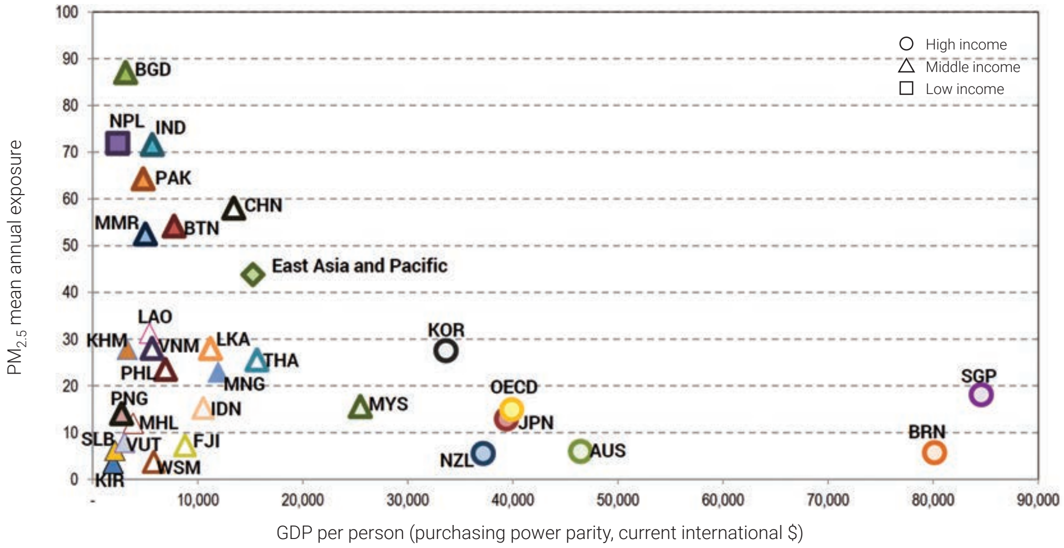
Many countries have sought to balance environmental and public health concerns with their economic growth. The Asia and Pacific region's total population grew at an annual rate of 1.21 per cent between 2000 and 2015 and by 2016 was home to more than 4.5 billion people, accounting for nearly 60 per cent of the world's population (UNESCAP 2016a). In 2015, the region's five most populous economies were China, 1.4 billion; India, 1.3 billion; Indonesia, 258 million; Pakistan, 189 million and Bangladesh, 161 million. Many countries in the region are still in the early stages of economic development, with policy makers facing a number of economic and environmental challenges, and trade-offs. Nonetheless, air pollution is progressing up the list of policy priorities everywhere, as reflected in the United Nations Environment Assembly resolutions on air quality (http://web.unep.org/environmentassembly/).

The combination of high population density, an energy-intensive economic structure, and high dependence on coal has led to serious air pollution problems. Many Asian cities have experienced severe air pollution, especially with $PM_{2.5}$. Only two of 230 Asian cities complied with the WHO Guideline in 2008 (CAI-Asia 2010), while average annual $PM_{2.5}$ levels in Asia have continued to exceed the annual WHO Guideline over the last two decades. This section examines how socio-economic development is coupled with, or decoupled from, air quality in Asian countries (Figures 1.15 and 1.16). A majority of low-income countries in this region are exposed to high $PM_{2.5}$ concentrations, except for Pacific island countries.

As shown in Figure 1.15, the $PM_{2.5}$ concentration stabilizes with economic growth, assuming that developing economies follow the previous pathways of other countries. Policy interventions have helped to break the historic link between economic growth and pollution and, with the policies that are already in place, countries can expect economic growth with no increase in air pollution. Examples of earlier decoupling of $PM_{2.5}$ concentrations and economic development are China, Indonesia, Pakistan, Sri Lanka, Thailand and Viet Nam (Figure 1.16).

Coal combustion is another major factor affecting air pollution in developing countries. A high proportion of coal in electricity generation contributes to high $PM_{2.5}$ concentrations in the region (Figures 1.17 and 1.18). Here again, however, many of the region's countries show earlier decoupling. In Indonesia, Malaysia, Philippines and Viet Nam, $PM_{2.5}$ concentrations have stabilized despite the increasing portion of coal in electricity generation. Australia has kept emissions low despite a high proportion of energy generation from coal and China recently introduced ultra-low emission control technologies for power plants as well.

Carbon dioxide emissions have a strong correlation with GDP (Figures 1.19 and 1.20). As shown earlier, although low- and middle-income countries improve air quality once a certain income level has been reached, CO_2 emissions continue to grow. Economic development often comes with high energy consumption. In most middle-income countries of



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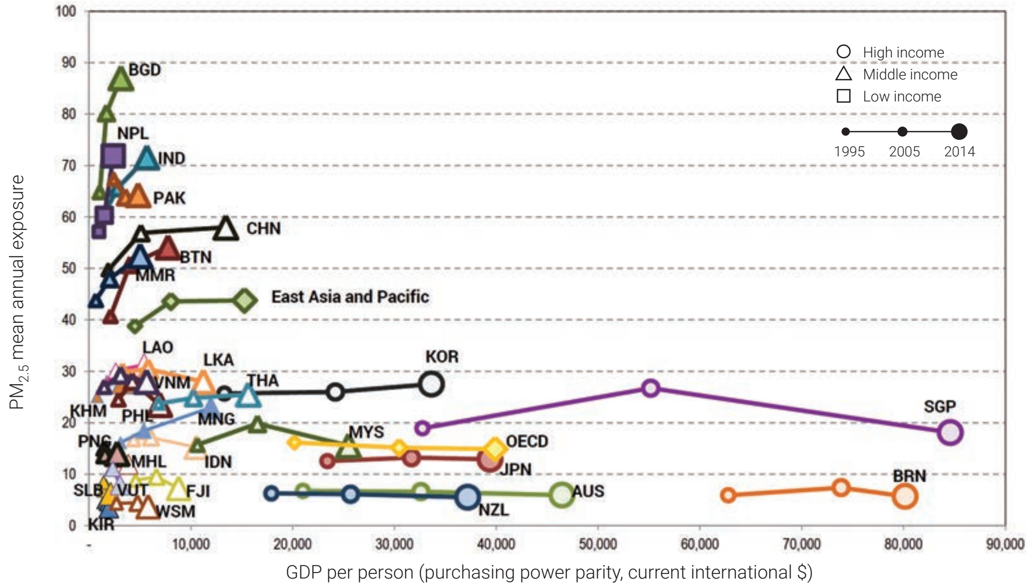
Note: World Bank's country code

Note: PM$_{2.5}$ mean is annual weighted population exposure from the GBD 2013 study (Brauer *et al*. 2016). Exposure is calculated by weighting mean annual concentrations of PM$_{2.5}$ by population in both urban and rural areas.

FIGURE 1.15: PM$_{2.5}$ CONCENTRATIONS AND GDP PER PERSON BY COUNTRY IN ASIA AND THE PACIFIC

Source: World Bank 2014a, 2014b



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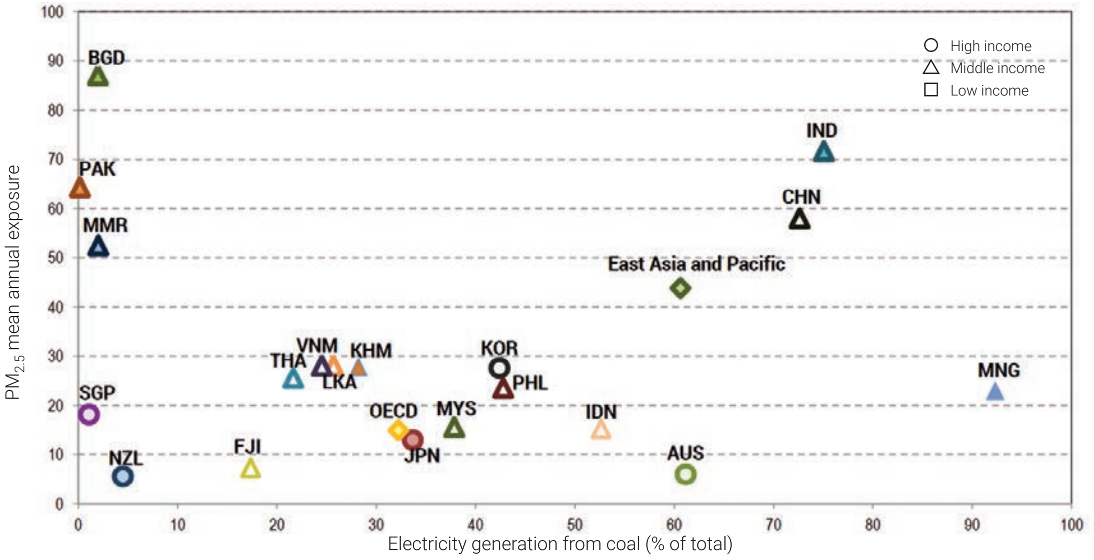
Note: PM$_{2.5}$ mean is annual weighted population exposure from the GBD 2013 study (Brauer *et al*. 2016). Exposure is calculated by weighting mean annual concentrations of PM$_{2.5}$ by population in both urban and rural areas.

FIGURE 1.16: PATHWAYS OF PM$_{2.5}$ CONCENTRATION AND ECONOMIC DEVELOPMENT BY COUNTRY IN ASIA AND THE PACIFIC

Source: World Bank 2014a, 2014b



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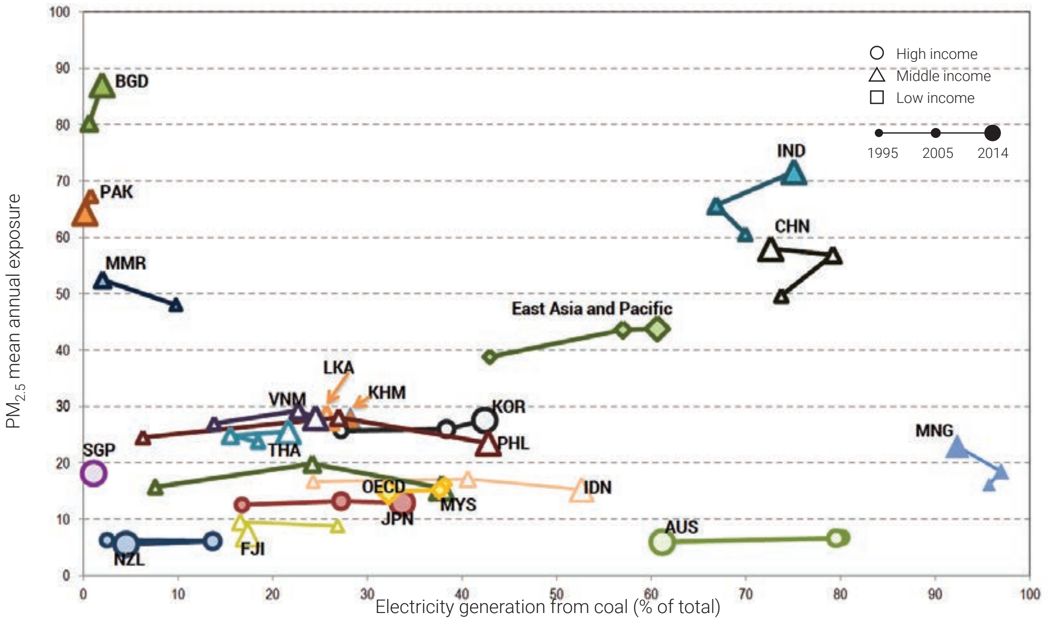
Note: World Bank's country code

Note: PM$_{2.5}$ mean is annual weighted population exposure from the GBD 2013 study (Brauer *et al*. 2016). Exposure is calculated by weighting mean annual concentrations of PM$_{2.5}$ by population in both urban and rural areas.

FIGURE 1.17: PM$_{2.5}$ CONCENTRATIONS AND THE PERCENTAGE OF ELECTRICITY GENERATED FROM COAL BY COUNTRY IN ASIA AND THE PACIFIC

Source: World Bank 2014a, 2014b



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Note: World Bank's country code

Note: PM$_{2.5}$ mean is annual weighted population exposure from the GBD 2013 study (Brauer *et al*. 2016). Exposure is calculated by weighting mean annual concentrations of PM$_{2.5}$ by population in both urban and rural areas.

FIGURE 1.18: PATHWAYS OF PM$_{2.5}$ CONCENTRATION AND THE PERCENTAGE OF ELECTRICITY GENERATION FROM COAL BY COUNTRY IN ASIA AND THE PACIFIC

Source: World Bank 2014a, 2014b

Asia and the Pacific, CO_2 emissions have increased as countries become wealthier. Thus, many have an undesirably high potential for further increases in CO_2 emissions, and it is likely that many of the region's rapidly growing economies will emit more $PM_{2.5}$ and CO_2 in the near future. However, high-income countries with low carbon-emission policies, such as Australia, Japan and New Zealand, show a decoupling of CO_2 emissions from GDP per person. In addition, some countries in the region have already shown earlier decoupling of $PM_{2.5}$ concentrations and coal consumption with economic development. Therefore, informed environmental policy decisions, along with a strong national mandate for sustainable growth, such as a continuing and increasing attention to clean energy, can reduce both air pollutant and CO_2 emissions. By taking these sustainable socio-economic development pathways, including clean fuel use and urban planning, countries in Asia and the Pacific may be able to continue on their road to developed-nation status and still be able to manage their local air quality as well as contribute to climate change mitigation by decreasing greenhouse gas emissions.

1.5.2 Air quality and sustainable cities

As mentioned in the previous section, the Asia and Pacific region was home to about 4.5 billion people in 2016. The extent of urbanization across sub-regions varies, with rates ranging from as high as 85 per cent in the Pacific to 34 per cent in Southeast Asia (Figure 1.21) (UNESCAP 2013), and by 2050 it is expected that two-thirds of the population in Asia and the Pacific will live in urban areas (UNESCAP 2014). Contributions to urban growth are varied, and sub-regional analysis tends to hide country-to-country realities. Nevertheless, general trends suggest high rates of urbanization across Asia and the Pacific. Pacific growth rates have limited impact due to their inherently small populations (UN-Habitat and UNESCAP 2015).

The region is also home to seven of the 10 most populous cities in the world (Wharton 2012) – Beijing, Delhi, Dhaka, Kolkata, Mumbai, Shanghai and Tokyo – and is projected to have 21 of 37 global megacities, those with populations of more than 10 million people, by 2025 (Figure 1.22) (ADB

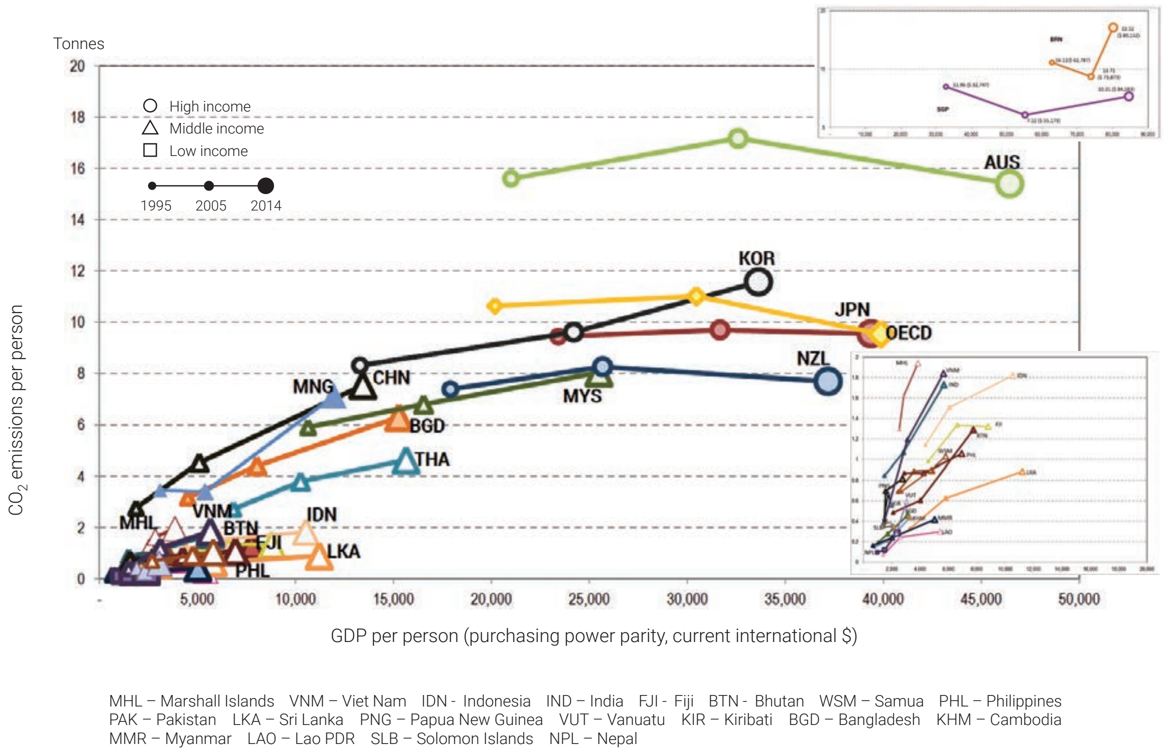
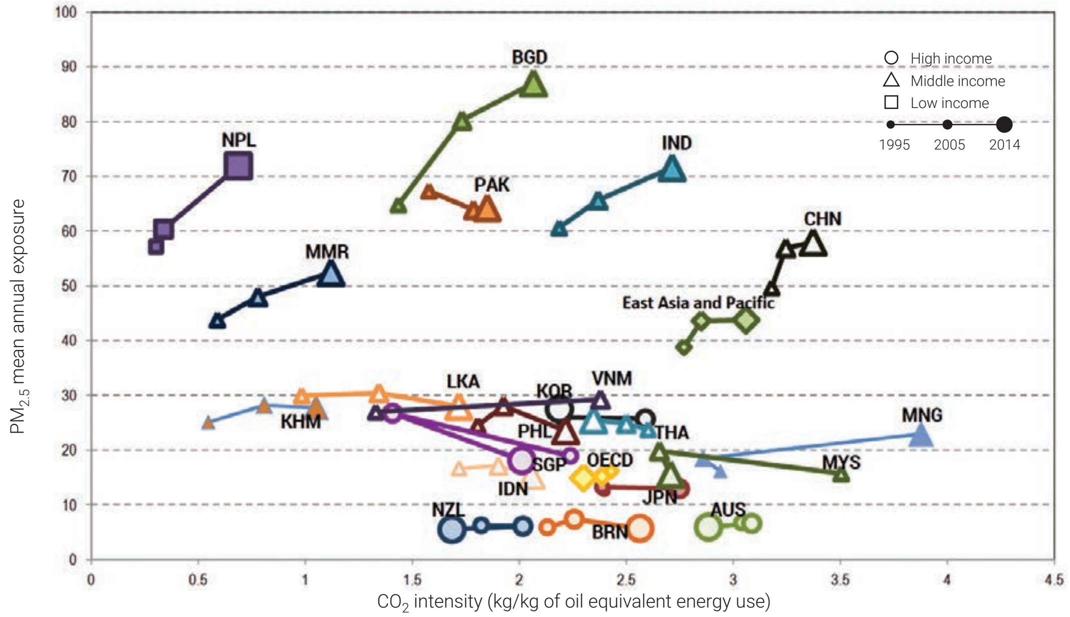


FIGURE 1.19: PATHWAYS OF CO_2 EMISSIONS AND ECONOMIC DEVELOPMENT BY COUNTRY IN ASIA AND THE PACIFIC

Source: World Bank 2014b



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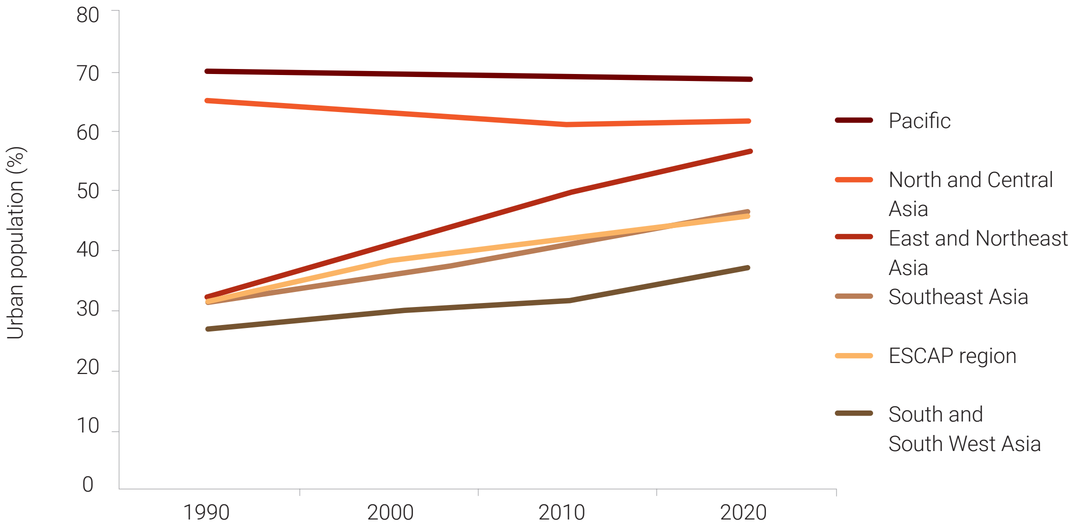
Note: PM$_{2.5}$ mean is annual weighted population exposure from the GBD 2013 study (Brauer *et al*. 2016). Exposure is calculated by weighting mean annual concentrations of PM$_{2.5}$ by population in both urban and rural areas.

FIGURE 1.20: PATHWAYS OF PM$_{2.5}$ CONCENTRATION AND CO2 INTENSITY BY COUNTRY IN ASIA AND THE PACIFIC

Source: World Bank 2014a, 2014b



Note: the geographic sub-regions shown here vary from those used in the present study.

FIGURE 1.21: URBANIZATION IN ASIA AND THE PACIFIC, 1990–2020

Source: UNESCAP 2013

2015). These cities are hubs of socio-economic and political activity in the region and serve as major drivers of the global economy (UNESCAP 2016a). Overall, the Asia and Pacific urban population provides 80 per cent of the region's GDP despite having about 40 per cent of the population (ADB 2012). Existing cities are also rapidly expanding to form mega-cities, urban corridors and city-regions. These urban configurations result in faster economic and demographic growth than that of the countries in which they are located (UN-Habitat 2016).

1.5.2.1 Urbanization as a key driver of air pollution and greenhouse gas emissions

Much of the growth and economic productivity of cities is closely tied to energy demand. Given the region's rapid expansion, the Asia Pacific Energy Research Centre expects energy demand to increase by 32 per cent by 2040, driven by the industrial, transport and residential sectors in relatively equal parts (APERC 2016). This has significant implications for air quality and greenhouse gas emissions given that the region's energy systems are largely based on fossil fuels (UNESCAP 2016b), particularly coal and natural gas (US EIA 2016).

Looking at transport, increased car ownership is strong in China, India and Southeast Asia. Road transport presents other challenges such as congestion and concentrated urban emissions in heavily populated areas, as well as significant contributions to $PM_{2.5}$ and NO_x levels due to the reliance on diesel fuel (IEA 2016).

Most cities are energy intensive, and Asian ones are no exception (UN-Habitat 2016). The IEA estimates that globally 85 per cent of particulate matter and a majority of sulphur oxides (SO_x) and NO_x are due to 'unregulated, poorly regulated or inefficient fuel combustion' resulting from the energy-use patterns arising from poverty, solid fuel use and urbanization (IEA 2016). Given the inherent high-energy use of cities and their reliance on fossil fuels, the majority of the people living in cities are exposed to unhealthy levels of air pollution every day. For Asia, seven in every 10 cities suffer from poor air quality. Most of these

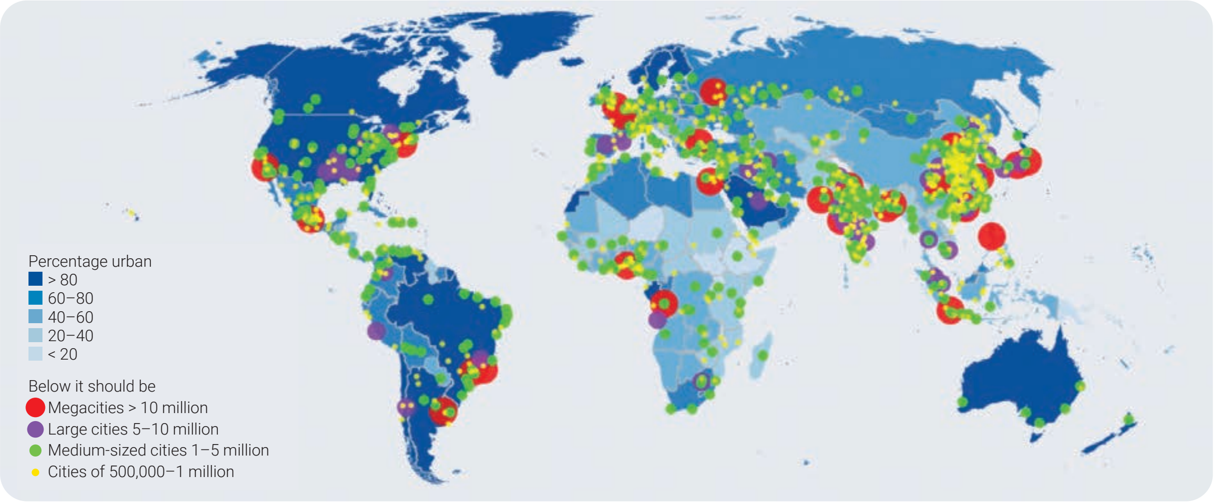


FIGURE 1.22: LOCATION AND SIZE OF URBAN AGGLOMERATIONS, AND COUNTRIES' URBAN POPULATION

Source: Enjie *et al*. 2015 (Figure is reproduced from United Nations Department of Economic and Social Affairs Population Division, 2014: https://esa.un.org/unpd/wup/Publications/Files/WUP2014-Report.pdf.)

cities exceed both the interim targets and the annual PM_{10} and $PM_{2.5}$ guideline values set by the WHO (Figure 1.23).

1.5.2.2 Air quality impacts on economies

Air quality is one of the main determinants of environmental quality in city competitiveness, as seen in the urban liveability ratings of the Economist Intelligence Unit, with Australian cities (EIU 2016) populating the top 10. Aside from infrastructure and mobility, air pollution is one of the main challenges in effective urban management (IEA 2016). Poor air quality has implications for local economies and job markets as measured through lost labour output, and acutely represented by South Asia, which loses as much as 0.83 per cent of its GDP to air pollution (Figure 1.24).

1.5.2.3 Regional issues impacting air quality

An important aspect of air pollution is transboundary haze emanating from the open burning of vast areas of forests and plantations in the region. Largely composed of $PM_{2.5}$ (ASEAN 2018), these fires are also responsible for about 40 per cent of Indonesia's overall greenhouse gas emissions (ESA 2002). Because of its proximity to urban centres, haze poses increased health risks for exposed populations, facilitates acid rain and affects economic activities. The 2015 haze episode in Singapore was estimated to have caused US$ 700 million of losses (Barratt 2016) (Box 1.5). Although the Association of Southeast Asian Nations (ASEAN) countries[1], particularly Indonesia, have passed several laws and policies to control the fires and address the transboundary problem – suspension of palm oil plantation licences, prosecution of offending parties and peatland conservation efforts (Lee and Shibao 2016) – results have been limited at best. The immense source of the problem calls for increased investment to achieve a successful outcome.

When strong, turbulent winds disturb land surfaces that are dry, unconsolidated (loose) and fine-grained with minimal or almost no vegetation cover, sand and dust storms can occur. This atmospheric phenomenon has hazardous health (section 1.2), agricultural (section 1.4.4) and socio-economic impacts for many countries in the Asia and Pacific region. Although partly a natural occurrence, sand and dust storms can be aggravated by unsustainable land and water management and particles can be transported over long distances. A recent policy review by Middleton and Kang (2017) concluded that they directly affect approximately 77 per cent of the countries that are Parties to the United Nations Convention to Combat Desertification (UNCCD), while only 23 per cent of them can be classified as source areas.

Aside from energy use, air pollution is largely determined by how geography and, by extension, climate conditions present distinct pollution challenges. To illustrate, Iran's capital Tehran suffers from severe air pollution episodes during winter. In November 2016, 400 people were reported to have died due to dense smog (Dehghan 2016). As a mountainous city with corresponding atmospheric conditions, transport and industrial emissions have led to severe episodes of air pollution. This is also common among landlocked cities in colder climates of Asia, such as Kabul, Afghanistan; Kathmandu, Nepal and Ulaanbaatar, Mongolia. Specifically, cities such as Kabul and Ulaanbaatar, which are both home to 55 per cent of the urban population in their respective countries, expose their populace to chronic diseases related to urban air pollution (UN-Habitat and UNESCAP 2015). On the other hand, due to their coastal nature, Pacific island countries are less affected by outdoor air pollution, despite concerns about rising vehicle emissions in urban areas (ADB 2012). Indoor air quality, however, is the relatively more urgent concern (section 1.2) as the use of traditional solid fuels such as wood is still prevalent (WHO 2002). Aside from this, air pollution has been linked to increased weather variability (Oskin 2014) (section 1.3).

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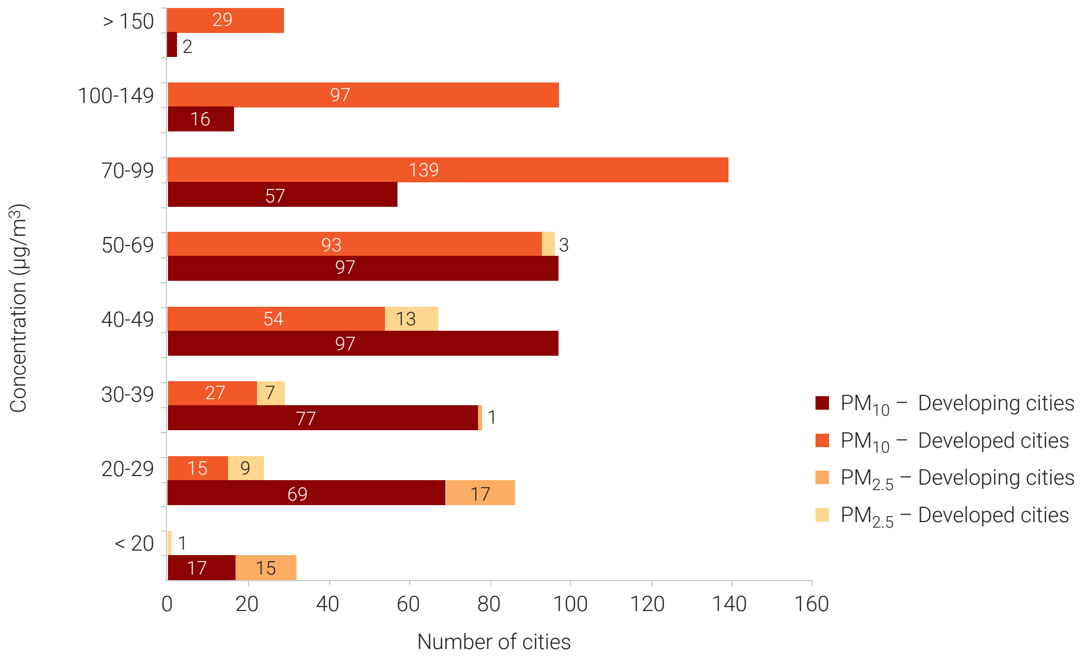
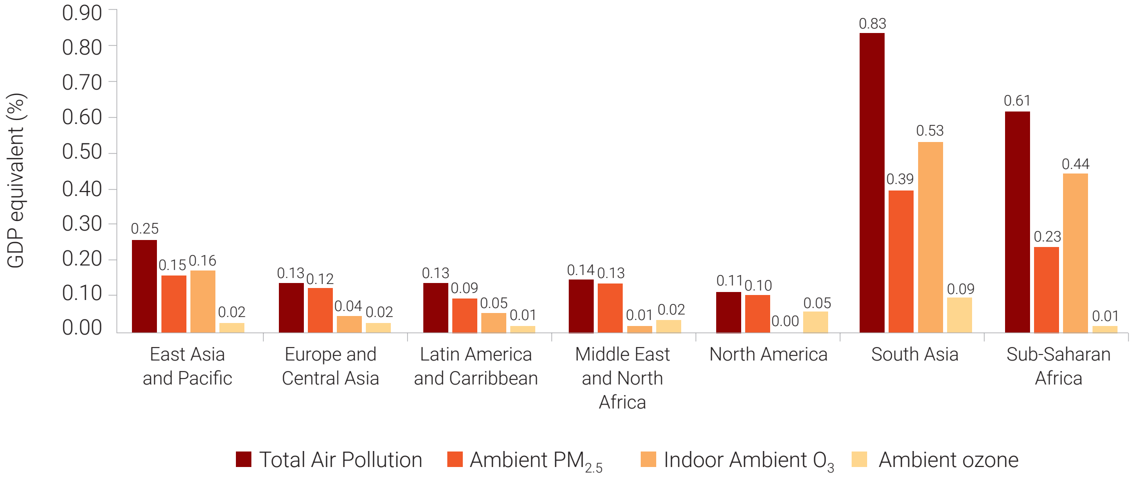
[1] ASEAN: Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Viet Nam.



Note: Data for the last available year in the period 2012–2016.

FIGURE 1.23: ANNUAL AVERAGE $PM_{2.5}$ AND PM_{10} CONCENTRATIONS IN ASIAN CITIES

Source: Data collected from publicly available sources compiled by WHO and Clean Air Asia



Note: Total air pollution damage includes ambient and indoor $PM_{2.5}$ and O_3.

FIGURE 1.24: LABOUR OUTPUT LOST DUE TO AIR POLLUTION, BY REGION, 2013

Source: World Bank Group and IHME 2016

BOX 1.5: REGIONAL HAZE EFFECTS IN SINGAPORE

Although the Singapore National Environment Agency tracks air pollutant data, it is unable to provide details of how much haze episodes contributed to the annual mean concentration of air pollutants. However, it is possible to make inferences based on the ambient level of pollutants of a year impacted by haze compared to one which is not. For example, the annual mean of $PM_{2.5}$ and PM_{10} in 2015, a year impacted by haze, was significantly higher than in 2016, a year not impacted by haze, as shown in the table below.

Pollutant	Averaging time	2015	2016	2020 air quality target[1]
PM_{10}	24-hour[3]	186	61	50
(µg/m^3)	Annual	37	26	20
$PM_{2.5}$	24-hour[3]	145	40	37.5
(µg/m^3)	Annual	24	15	12
Ozone	8-hour[2]	152	115	100
(µg/m^3)				
NO_2	1-hour[2]	99	123	200
(µg/m^3)	Annual	22	26	40
CO	1-hour[2]	3.5	2.7	30
(mg/m^3)	8-hour[2]	3.3	2.2	10
SO_2	24-hour[2]	75	61	50
(µg/m^3)	Annual	12	13	15

The Pollutants Standard Index (PSI) for Singapore also shows that the percentage of days with unhealthy air quality in 2015 was higher than in 2016 – the PSI includes SO_2, PM_{10}, $PM_{2.5}$, NO_2, CO and O_3. Beyond health implications, haze pollution also has significant economic costs and impacts on climate change. According to the World Bank, the 2015 haze episode cost Indonesia at least US$ 16.1 billion, equivalent to 1.9 per cent of Indonesia's 2015 GDP[a]. Domestically, the 2015 haze episode cost Singapore an estimated SG$ 700 million in losses[b]. There is also an ongoing regional study to assess the economic, social and health impacts of haze for Southeast Asia, which will allow affected countries to better understand the impact of transboundary haze and supplement existing estimates on the cost of the 2015 haze episode[c].

Apart from particulate matter, forest fires are also a major source of the greenhouse gas CO_2, thus contributing to climate change. The 2015 haze episode saw a huge release of natural carbon stores, particularly from the burning of peatland. According to the World Resources Institute, daily estimated greenhouse gas emissions from fires in Indonesia exceeded the average daily CO_2 emissions of the entire US economy (15.95 million tonnes of CO_2 per day) on 26 out of 44 days from early September to mid-October 2015[d]. A recent study conducted by scientists from the UK, Indonesia and the Netherlands concluded that the 2015 forest fires in Indonesia had generated about 850 million tonnes of CO_2, with daily emissions from September to October 2015 exceeding the combined emissions of the European Union during the same period[e].

Notes: [1] Singapore's 2020 air quality targets are benchmarked against the WHO's Interim Targets and air quality guidelines. For SO_2 and $PM_{2.5}$, Singapore's Sustainable Blueprint 2020 annual targets are 15µg/m^3 and 12µg/m^3 respectively. [2] Maximum 24-hour, 8-hour or 1-hour. [3] 99th percentile.

BOX 1.5: REGIONAL HAZE EFFECTS IN SINGAPORE (contd.)

[a] http://documents.worldbank.org/curated/en/776101467990969768/The-cost-of-fire-an-economic-analysis-of-Indonesia-s-2015-fire-crisis;
[b] http://www.channelnewsasia.com/news/singapore/haze-episode-cost-singapore-estimated-s-700m-last-year-masagos-8147924;
[c] http://www.straitstimes.com/singapore/environment/regional-study-to-be-done-on-economic-health-and-social-impact-of-haze-in-2015;
[d] http://www.wri.org/blog/2015/10/indonesia%E2%80%99s-fire-outbreaks-producing-more-daily-emissions-entire-us-economy;
[e] https://www.reuters.com/article/us-indonesia-haze/southeast-asian-fires-emitted-most-carbon-since-1997-scientists-idUSKCN0ZE210. Further information on air quality and haze can also be found in the National Environment Agency (NEA)'s website (http://www.haze.gov.sg/air-quality-information).

(Notes a–e are un-peer reviewed sources)

1.5.3. Air quality and the Sustainable Development Goals

A recent study estimates that deaths induced by air pollution cost the global economy about US$ 225 billion in lost labour income in 2013 (World Bank Group and IHME 2016). For sustainable economic growth, air quality management is becoming one of the most important concerns in the world. According to the US Environmental Protection Agency, air quality management is defined as all activities stemming from regulatory authority to protect human health and the environment from the harmful effects of air pollution. In terms of government, it refers to policy support to reduce air pollution. Various governmental policies aimed at improving air quality have achieved noteworthy outcomes. Many current air quality improvement measures, however, seem to have reached their limitations, especially for O_3 and particulate matter, due to a myriad of complex factors, including the soaring numbers of vehicles and the chemical production and transport of these pollutants in the atmosphere over large distances (General introduction, Figures A and B).

While a number of studies have estimated the cost of ambient air pollution (OECD 2016; World Bank Group and IHME 2016; OECD 2014), only two studies have carried out comprehensive cost-benefit analyses of air quality management policies in the Asia and Pacific region. Some studies on the cost-benefit analysis and welfare cost of air pollution reduction policies are reported in Tables 1.3 and 1.4.

Crane and Mao (2015) provided rough estimates of the potential costs to China of adopting extensive additional measures to reduce air pollution. Even though they did not investigate the impact of each policy on urban air pollution, the total benefit of pollution control policies exceeds three times that of the costs. Gao *et al.* (2016a) conducted a cost-benefit analysis of implementing industrial energy-saving and emission-reduction policies in 31 provinces for the period of 2013–2017. In this study, they also carried out a scenario analysis to assess the cost-effectiveness of individual energy-saving measures and emission reduction policies. Chae and Park (2011) also quantified costs and benefits of air quality management policies in the Seoul Metropolitan Area of the Republic of Korea with several different emission reduction scenarios. Even though their results indicate that reduction policies in Seoul are cost-effective, typical benefit-cost ratios cannot be generalized since they do not follow a conventional cost-benefit analysis framework.

Although there are positive benefit-cost results and accelerated implementation of many air pollution control measures in countries such as China, according to projections of the Organisation for Economic Co-operation and Development (OECD), a significant increase in global emissions of air pollutants is expected due to economic growth and energy demand. Consequently, this will be a tremendous regional burden in attaining sustainable development.

TABLE 1.3: COST-BENEFIT ANALYSES OF AIR QUALITY MANAGEMENT STUDIES

Policy measure	Sector	Pollutant	Country	B/C (ratio)	Study
Replacing coal with natural gas	Residential, commercial	SO_x, PM, NO_x	China	Approximately 3 times cost	Crane and Mao (2015)
Replacing coal-fired electricity with other fuels	Power generation	SO_x, PM, NO_x	China	Approximately 3 times cost	Crane and Mao (2015)
Scrapping older vehicles	Transportation	SO_x, PM, NO_x	China	Approximately 3 times cost	Crane and Mao (2015)
Energy-saving	All sectors	SO_2, NO_x, PM_{10}	China	Yuan 146 billion (NPV)	Gao *et al.* (2016)
End-of-pipe treatment	All sectors	SO_2, NO_x, PM_{10}	China	Yuan 516 billion (NPV)	Gao *et al.* (2016)
Integrated policies	All sectors	SO_2, NO_x, PM_{10}	China	Yuan 629 billion (NPV)	Gao *et al.* (2016)
Light-duty vehicle emission standards	Transportation	$PM_{2.5}$, O3, NO_2	China, Guangdong	More than 3 times	Shao *et al.* (2017)
Integrated policies	All sectors	NO_x, PM_{10}, CO_2	Republic of Korea	-	Chae and Park (2011)

NPV – net present value

The growing problem of poor air quality and the linked climate-driven impacts represent a tremendous regional burden and substantial barrier to attaining sustainable development. While there is no explicit reference to air pollution or air quality management in the 17 SDGs, the consequences and sources of air pollution impact many of them (Figure 1.25). Failure to address air pollution will directly threaten the success of SDG 3 which aims to 'ensure healthy lives and promote well-being for all at all ages', SDG 11 that aims to 'make cities and human settlements inclusive, safe, resilient, and sustainable', and SDG 12 on 'responsible consumption and production'. Moreover, the success of SDG 13 on climate action is inherently linked with air pollution due to common emission sources of air pollutants and greenhouse gases and their overlapping, nonlinearly associated impacts on climate, human health, agriculture and ecosystems (Melamed *et al*. 2016).

Despite its inherent complexities and projected difficulties related to effective implementation of appropriate measures, air quality management is just too important to dismiss as it is a critical component of sustainable development.

1.5.4 Conclusions

- Considerable reductions in pollution have been achieved in Asia and the Pacific, where policy interventions have helped break the historical link between economic growth and pollution. Informed policy decisions along

TABLE 1.4: TOTAL WELFARE COSTS OF AIR POLLUTION, CENTRAL PROJECTION (2010 US$)

	OECD		World	
	2015	2060	2015	2060
TOTAL market impacts (US$ billions)	90	390	330	3,300
Share of income (%)	0.3	0.5	0.6	1.5
Per person (US$)	70	270	50	330
TOTAL market impacts (US$ billions)	1,550	3,750–3,850	3,440	20,540–27,570
Share of income (%)*	5.0	5.0	6.0	9–12
Per person (US$)	1,210	2,610–2,680	470	2,060–2,770

* Welfare costs from non-market impacts are not related to expenditures and therefore not an integral part of the calculation of income; the expression of these welfare costs as share of income is therefore only for illustrative purposes.
Source: OECD 2016

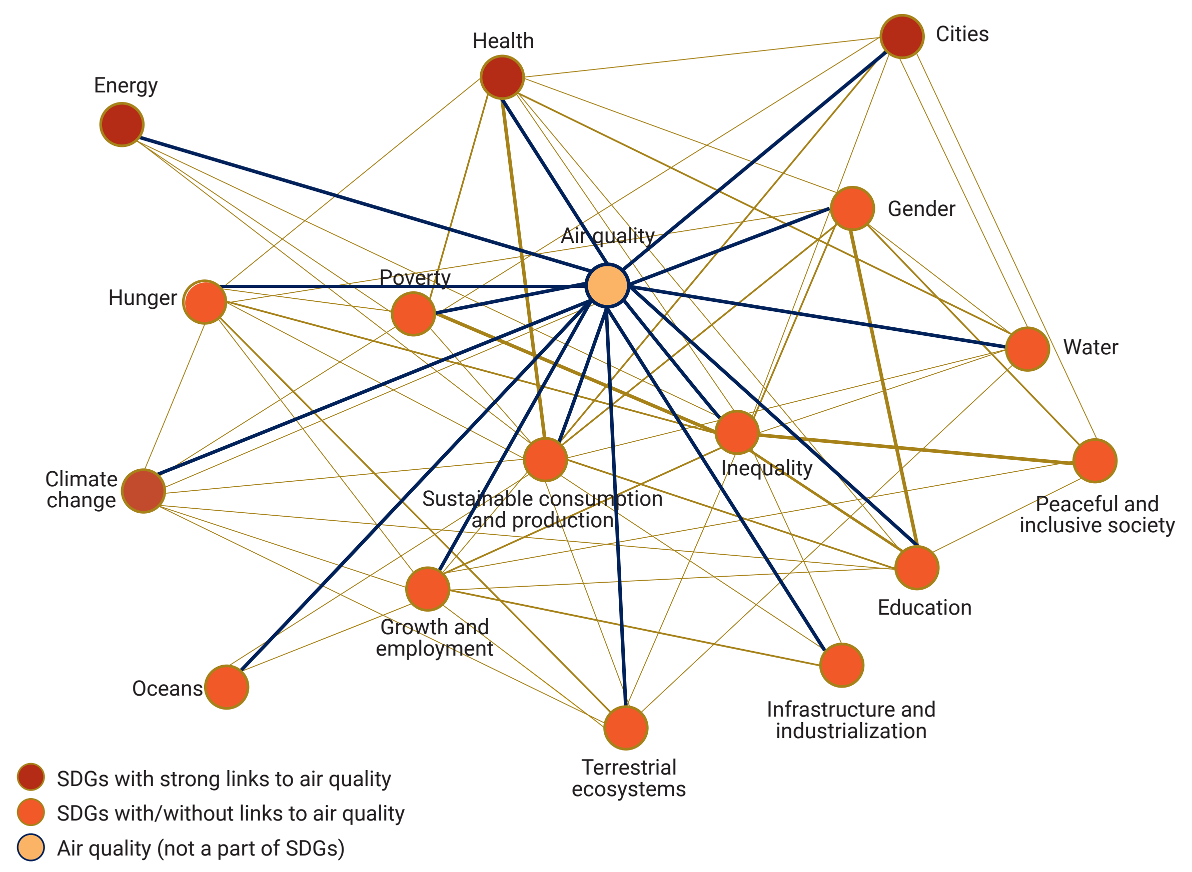


FIGURE 1.25: LINKS BETWEEN AIR QUALITY AND THE SUSTAINABLE DEVELOPMENT GOALS

Source: modified from Le Blanc 2015

with a strong national mandate for sustainable growth, such as a continuing and increasing attention to clean energy, have the potential to reduce both air pollutant and CO_2 emissions, while facilitating high levels of economic growth to reduce poverty.

- A number of cost-benefit studies in Asia show that the total benefits of pollution control policies greatly exceed their costs. Although there is accelerated implementation of many air pollution control measures in countries, a significant increase in emissions of air pollutants is expected due to economic growth and energy demand. Consequently, this will be a tremendous regional burden in attaining sustainable development.

- The economic development of the region's 41 countries varies widely, with national GDPs ranging from hundreds of dollars per person per year to more than US$ 80,000. The data suggest that high-income countries in the region have annual average population-exposure air pollution levels below 30 µg/m^3 of $PM_{2.5}$ and that trends from 1995 to 2014 are stable. There are few data available on low-income countries. Middle-income countries have quite variable annual average $PM_{2.5}$ concentrations, ranging from about 5µg/m^3 to more than 85 µg/m^3.

- Air quality is one of the main determinants of environmental quality in city competitiveness, as seen in the urban liveability ratings. Cities that wish to be globally competitive need to consider air quality as a serious issue.

- Further action is still needed to move towards air quality levels that conform to WHO guidelines for public health protection. These guidelines are aligned with the national air quality standards adopted by countries in Asia and the Pacific. Further action should reflect the diversity of the region in terms of stages of development, levels of capacity and availability of resources.

CHAPTER 2

Scenarios and solutions

2.1 INTRODUCTION

2.1.1 Modelling the region

The modelling studies reported in this chapter were conducted using data on emissions and ambient concentrations of the relevant pollutants in Asia. The absence of data of a suitable quality for large areas of the Pacific prevented modelling to the necessary level of reliability for the entire Asia and Pacific region.

Results are presented as aggregates for four sub-regions (Figure 2.1). While broadly based on the sub-regions defined by the UN Environment Asia and Pacific Office, countries were re-grouped for the purposes of modelling to take account of the availability of data and ensure the scientific consistency of the modelling results. These sub-regions are used for scientific convenience and have no official or administrative significance, and are composed as follows:

- East Asia (modelled East Asia) includes China, Democratic People's Republic of Korea and Mongolia (and excludes Japan and Republic of Korea);
- Southeast Asia (modelled Southeast Asia) includes Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Thailand and Viet Nam (and excludes Brunei Darussalam and Singapore);
- South Asia (modelled South Asia) includes Afghanistan, Bangladesh, Bhutan, India, Iran, Maldives, Nepal, Pakistan and Sri Lanka;
- High-income countries (modelled high-income countries) include Brunei Darussalam, Japan, Republic of Korea and Singapore.

2.1.2 Background

Rapid economic growth has led to high levels of air pollution throughout Asia, causing social, public health and environmental problems that add to the challenges of sustainable development. Many Asian countries have initiated action to reduce emissions of air pollutants; often, however, their benefits are counteracted by further economic growth and are therefore not always visible.

World-wide experience clearly demonstrates that clean air can be achieved without compromising social and economic development. To be most successful, this requires well-designed policies that prioritize, for specific conditions, cost-effective interventions for the sources that deliver the largest benefits, and that are well integrated with other development targets. This assessment highlights how much progress has been made in Asia in decoupling air pollution trends from economic growth (Figure 2.4), and demonstrates a clear potential for further progress in line with aspirations for sustainable development and protection of human health and the environment, including the climate.

While there is ample experience from Europe, North America and other areas that could help improve the situation in Asia further, this cannot be directly transferred to Asia due to differences in economic development, social conditions, meteorological factors and institutional settings.

With a focus on Asia, this chapter presents an analysis of promising air quality management options that could effectively improve air quality in Asia and contribute tosustainable economic development.

The objective of this chapter is to identify concrete air quality management options that can provide optimum benefits in the wider context of sustainable development, using robust science and a comprehensive approach. It is organized as follows: the first section introduces the conceptual framework that has been used for the assessment of effective policy intervention options and briefly introduces the tools and assumptions that have been employed. Subsequently, the chapter presents key findings, with graphs and some explanatory notes. More detailed information is provided in Annex 2.1.

2.2 APPROACH AND METHODOLOGY

2.2.1 Air quality management options with multiple benefits for development

This chapter explores air quality management options for Asia with simultaneous benefits for air quality and other development objectives (Figure 2.2).

- First, the analysis explores the factors that determined the historic development of air pollutant emissions in Asia, and extrapolates emissions up to 2030, taking into account emissions control legislation that has already been implemented or adopted by Asian countries.

- Second, it assesses the scope for further reductions in air pollutant emissions from three sets of measures:
  - a full Asia-wide application of the measures that proved effective in the past for Asian conditions;
  - next-stage Asia-specific air quality measures that address the remaining priority emission sources in Asia;
  - other measures that contribute to development priorities.

- Third, the chapter determines for these three portfolios the impacts of each measure on population exposure to harmful fine particulate matter ($PM_{2.5}$) in Asia and identifies those measures that deliver the greatest benefits.

- Finally, the impacts of these measures on human health, agricultural crop yields and temperature increase are assessed, and their contributions to the achievement of the Sustainable Development Goals (SDGs) are characterized in qualitative terms.

Integrated perspective based on state-of-the-art methods

Identifying promising policy intervention options that could deliver effective improvements in air quality in Asia together with progress towards the SDGs requires an holistic perspective that integrates geo-physical, economic, social and institutional dimensions across different spatial and temporal scales. This analysis achieves such a perspective through a suite of well-established scientific tools that cover the different elements (Box 2.1).

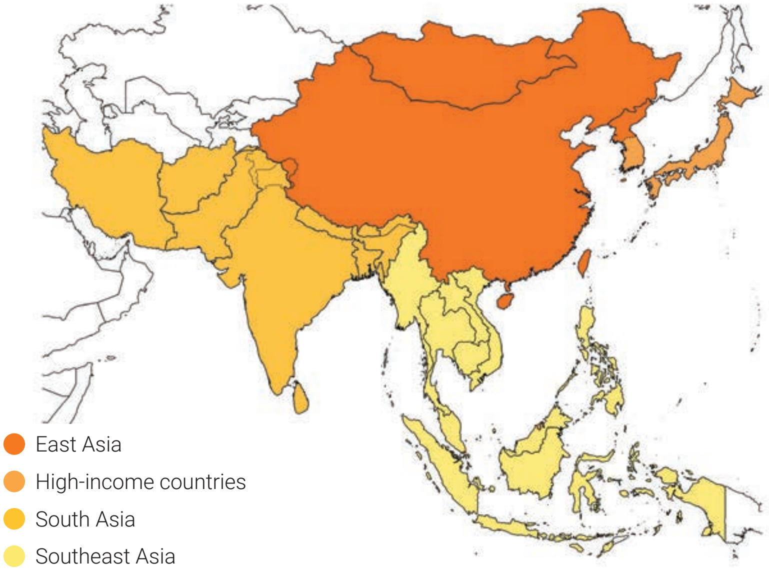


FIGURE 2.1: MODELLED SUB-REGIONS OF ASIA

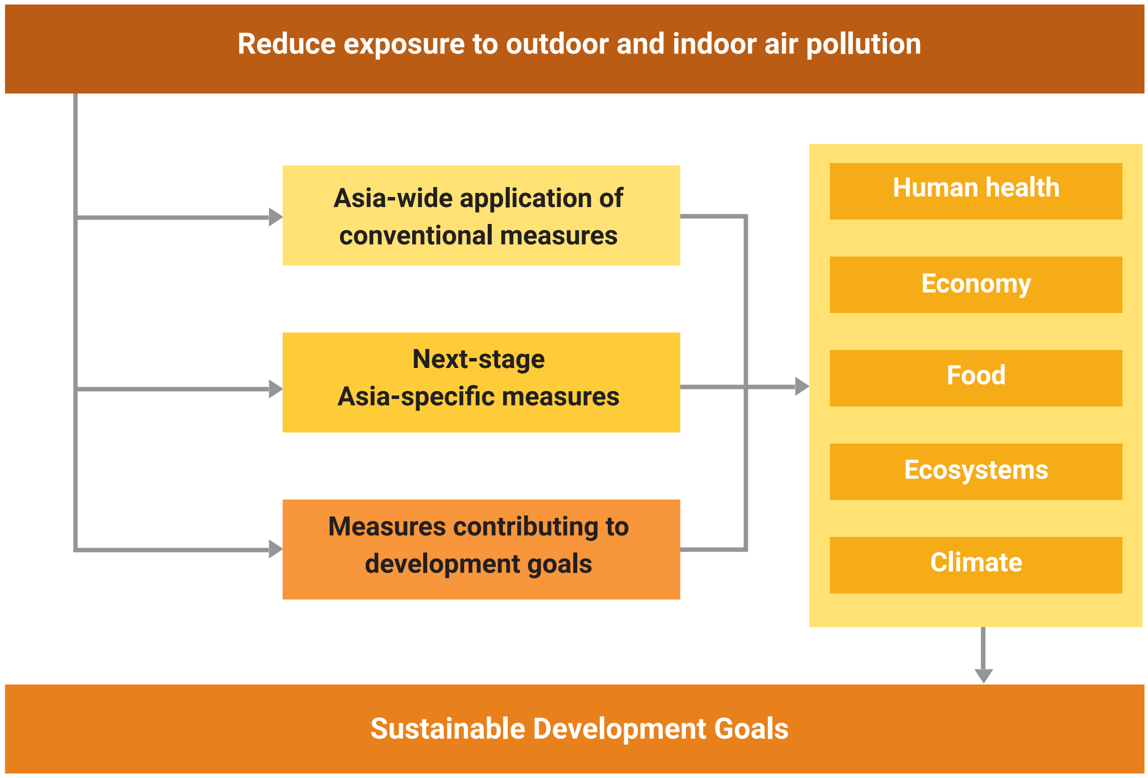


FIGURE 2.2: CONCEPTUAL APPROACH FOR IDENTIFYING EFFECTIVE AIR QUALITY MANAGEMENT MEASURES THAT ALSO CONTRIBUTE TO THE CLIMATE AND SUSTAINABLE DEVELOPMENT AGENDAS

Capturing diversity for tailored findings

Diversity is a distinguishing feature of Asia. As a consequence, any effective clean air strategy will vary in approach based on the context of each country and/or city, as well as its capacity to develop and implement measures. There is no uniform policy prescription for air quality that is applicable to all countries and regions; such an approach would neither be possible nor desirable for a problem that is so diverse in local circumstances.

To capture the multiple dimensions of Asian diversity, the current analysis was carried out for 100 emission source regions in Asia, distinguishing the individual states and provinces of large countries, as well as megacities (Annex 2.1). Impacts on ambient air quality and population exposure were computed for 1,275 individual cities, as well as for rural areas with a spatial resolution of 0.5 x 0.5 degrees – approximately 40 x 50 kilometres (km).

2.3 KEY FINDINGS

2.3.1 Success in breaking the historic link between economic growth and pollution

From 1990 onwards, all $PM_{2.5}$ precursor emissions in Asia grew steadily. Particularly large increases occurred for sulphur dioxide (SO_2) and nitrogen oxides (NO_x), which closely followed the expansion of economic activity as measured by gross domestic product (GDP). Emissions for which non-industrial sources are more important, such as volatile organic compounds (VOCs) and primary emissions of $PM_{2.5}$ from residential combustion of biomass, or ammonia (NH_3) from agricultural activities, developed along less steep growth paths (Figure 2.4).

After 2005, however, policy interventions – especially sulphur controls at power plants in China and the introduction of emissions standards for vehicles –

BOX 2.1: MODELLING TOOLS USED IN THIS ANALYSIS

The analysis employs a series of well-established scientific tools and methods that put the relevant aspects in context with each other for the quantification of potential benefits (Figure 2.2).

The Greenhouse gas – Air pollution Interactions and Synergies (GAINS) model (Amann *et al*. 2011) quantifies the drivers, mechanisms and impacts of emissions, and explores options for reducing impacts in cost-effective ways. Projections of future economic activity, energy use and agricultural production are derived from the analyses of the International Energy Agency (IEA), presented in its 2016 World Energy Outlook Special Report: Energy and Air Pollution (IEA WEO 2016), and the Food and Agriculture Organization of the United Nations (FAO). Current emissions are estimated based on international activity statistics, with emission factors reflecting local conditions in 100 regions of Asia. Considering about 2,000 emission reduction options, their impacts on ambient air quality and population exposure are computed for 1,275 urban areas across Asia and surrounding rural regions, based on the results of the European Monitoring and Evaluation Programme (EMEP) atmospheric chemistry and transport model (more details are provided in Annex 2.1).

As an indicator for population exposure to particulate matter (PM), this report employs the annual average population-weighted mean exposure to ambient $PM_{2.5}$, accumulated over the full population, as the central metric. Following the method adopted by the World Health Organization (WHO) for the 2016 Global Burden of Disease study (WHO GBD 2016), health impacts from exposure to $PM_{2.5}$ and ozone (O_3) in ambient air and to indoor pollution are quantified, and their uncertainties estimated with alternative parametrizations that have been used for similar assessments. The analysis in this report is restricted to premature mortality and does not address the morbidity impacts of pollution.

The impacts of emission changes on temperature increase and other climate indicators are calculated with the Goddard Institute for Space Studies (GISS) and Goddard Earth Observing System (GEOS-Chem) models of the National Aeronautics and Space Administration (NASA) (Schmidt *et al*. 2014; Shindell *et al*. 2013), and a parametrization using the Absolute Global Temperature Potential (AGTP) (Shindell 2015). Crop losses from O_3 are estimated based on standard global DO3SE methods used by the Stockholm Environment Institute (SEI). Further details are provided in Annex 2.1.

led to a distinct decoupling of SO_2 and NO_x emissions from economic growth, while $PM_{2.5}$ emissions remained relatively flat[1] (Figure 2.4). In contrast, in the absence of policy interventions, emissions of NH_3 continued to grow as a consequence of increasing agricultural production.

By 2015, SO_2 emissions in Asia had declined by 15 per cent relative to 2005, despite the 63 per cent growth in GDP. Without the implementation of control measures, emissions would have been 80 per cent higher, and without the energy policy measures 95 per cent higher. Nitrogen oxide emissions grew by 27 per cent, with emission controls avoiding a further 22 per cent increase.

Energy policy, especially the shift from coal and biomass to cleaner fuels, avoided a 50 per cent increase in primary emissions of $PM_{2.5}$, and dedicated pollution controls avoided a 20 per cent growth (Figure 2.7). Together, these policy interventions resulted in a stabilization of $PM_{2.5}$ emissions.

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[1] The trends for Asia illustrated in Figure 2.4 are largely driven by recent policy developments in China; the trends for the four modelled sub-regions of Asia (Figure 2.3) are shown in Figure 2.28.

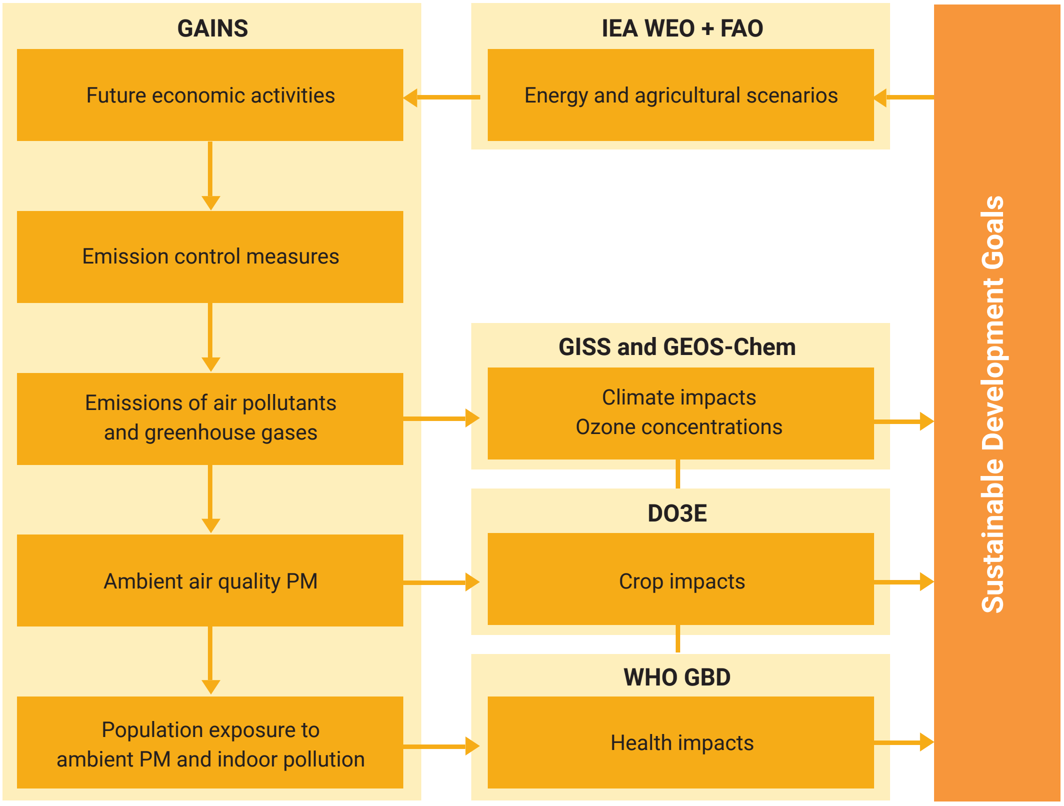
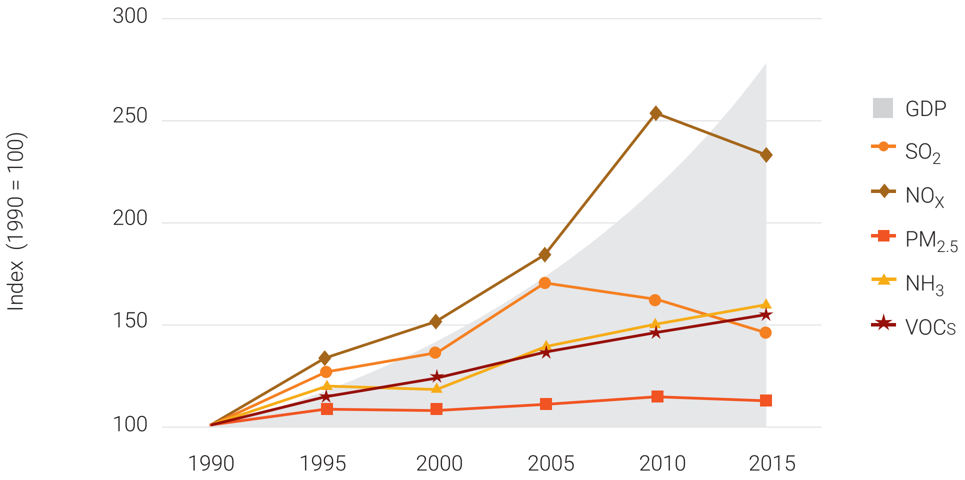


FIGURE 2.3: THE SUITE OF MODELS USED FOR THIS ANALYSIS AND THE INTERACTIONS BETWEEN MODELS



SO_2 – sulphur dioxide; NO_x – nitrogen oxides; NH_3 – ammonia; VOCs – volatile organic compounds

FIGURE 2.4: THE EVOLUTION OF GDP AND THE POLLUTANTS THAT CONTRIBUTE TO $PM_{2.5}$ FORMATION IN ASIA, 1990–2015

Source: IEA WEO 2016; GAINS model estimates

2.3.2 Measuring atmospheric pollutants

While monitoring data are not available for all cities and locations in Asia, air quality across Asia can be modelled with atmospheric chemistry-transport models using the best information available on emissions and meteorological conditions.

For 2015, particularly high levels were calculated for urban and heavily industrialized areas with high population densities, for example in many cities in the northeast of China and in the Ganges valley (Figure 2.5). In addition, high concentrations occurred in areas with large sources of natural soil dust from drylands such as the Gobi Desert and in large parts of western Asia.

The 2015 concentrations shown in Figure 2.5 were computed with the GAINS model, using emission estimates developed for the model (Klimont *et al.* 2017; IEA WEO 2016; Klimont *et al.* 2013). Results agree well with observations as well as with other model calculations, such as the NAQPMS model of the Institute of Atmospheric Physics of the Chinese Academy of Sciences (CAS) in Beijing, and the MICS-Asia model inter-comparison for Asia (Gao *et al.* 2018); see Annex 2.1 for a detailed comparison.

Pollutant levels continue to exceed national and international air quality standards

Despite the recent declines in total SO_2 and NO_x emissions, a large quantity of air quality monitoring data provides ample evidence that national and international air quality standards (Table 2.1) are currently widely exceeded in Asia. Model calculations that cover all of Asia indicate that $PM_{2.5}$ concentrations in ambient air exceeded the international WHO Guideline value of 10 micrograms per cubic metre (µg/m^3) over large areas, and essentially in all populated regions (Figure 2.5). Furthermore, concentrations exceeded the highest WHO Interim Target level 1 (35 µg/m^3) in many areas.

In 2015, less than 8 per cent of the Asian population enjoyed air quality that conforms to the WHO Guideline

A comparison of the $PM_{2.5}$ fields with population data reveals that in 2015 less than 8 per cent of the Asian population could breathe air that conforms to the WHO Guideline for $PM_{2.5}$ of 10 µg/m^3. In contrast, more than half of the Asian population, about 2.3 billion people, faced exposure that exceeded even the highest WHO Interim Target of 35 µg/m^3 (Figure 2.6). Between 2005 and 2015, population-weighted mean exposure increased by about 10 per cent and reached 43 µg/m^3, more than four times the WHO Guideline value.

In addition, in 2015 almost 1.9 billion people suffered from exposure to indoor pollution as a consequence of burning solid biomass or coal in cookstoves.

2.3.3 Energy policy and pollution control

Many Asian countries have established ambitious targets for reducing the energy intensity of their economies through dedicated energy efficiency policies and a restructuring of production towards less energy-intensive products, meaning that in the future, energy consumption trends will decouple from economic growth even more than in the past. In addition, countries are aiming to transform their energy systems, with a less prominent role for fossil fuels such as coal and oil. As a consequence, the recent projections of future energy use published by the IEA (IEA WEO 2016) foresee growth in total primary energy consumption of 25 per cent between 2015 and 2030, much less than the 80 per cent increase in GDP that is assumed for the same period.

Energy policy and the enforcement of strengthened pollution control measures will remain key determinants for a further decoupling between economic growth and pollution in Asia

However, despite these energy policies, the 25 per cent higher energy consumption will further enhance the pressure on air quality in Asia. Technical means exist to reduce emissions, and important measures have already been adopted by legislation that should lead to lower emissions in the future if they are effectively implemented.

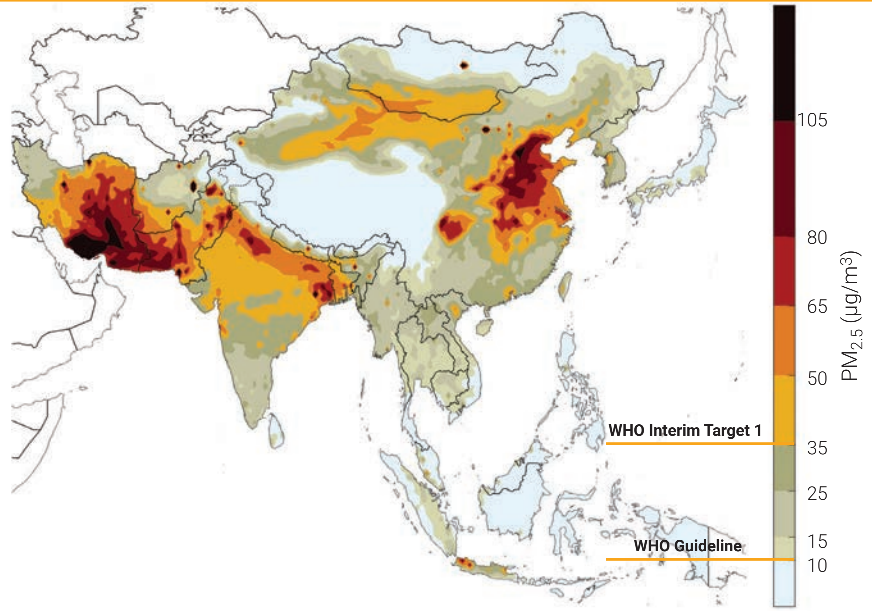


FIGURE 2.5: AMBIENT LEVELS OF $PM_{2.5}$ IN ASIA IN 2015

Source: GAINS 2017

TABLE 2.1: NATIONAL AIR QUALITY AND GLOBAL GUIDELINES FOR $PM_{2.5}$

	Annual mean $PM_{2.5}$ concentration	**WHO Air Quality Criteria**	**National air quality standards**
●	40 µg/m^3		India
●	35 µg/m^3	WHO Interim Target 1	China Grade II[a] Malaysia
●	25 µg/m^3	WHO Interim Target 2	Mongolia Philippines Sri Lanka Thailand Viet Nam
●	15 µg/m^3 12 µg/m^3	WHO Interim Target 3	Bangladesh China Grade I[b] Indonesia Japan Pakistan Republic of Korea Singapore
●	10 µg/m^3 8 µg/m^3 [c]	WHO Guideline	Australia

[a] Natural Protection Area and other areas which need special protection
[b] Residential, commercial, industrial and rural area
[c] Maximum concentration

In addition, a wealth of further measures, often for emission sources that are not addressed by current legislation, could deliver substantial additional emission reductions throughout Asia.

The effectiveness of implementation and enforcement of existing control measures will have a crucial impact on future emission levels. By 2030, without the policies and measures put in place and enforced in the last decade, SO_2 emissions in Asia would likely be almost three times greater than in 2015, given the expected further 80 per cent increase in GDP. However, the measures introduced after 2005 cut emissions by about 40 per cent by 2015 and will continue to do so in future if effectively enforced. Together with current energy policy measures – to reduce energy intensity and phase out solid fuels – they would limit the emissions increase in 2030 to about 20 per cent compared to 2015. If all countries enforced the emission controls that they have already included in their legislation but that are not yet implemented, Asian SO_2 emissions would shrink by 20 per cent from 2015 levels. Full application of all available controls could cut SO_2 emissions by 60 percent (Figure 2.7).

A similar picture emerges for emissions of NO_X, which would be 100 per cent higher by 2030 compared with 2015 levels in the absence of any emission controls. Energy policy measures together with existing emission controls would limit the increase in emissions to 25 per cent above 2015 levels, while a timely enforcement of recent legislation would deliver a 15 per cent reduction in emissions compared with 2015 levels. Overall, there is scope for a 50 per cent reduction in emissions of NO_x compared with 2015.

Primary emissions of $PM_{2.5}$ would double by 2030 compared with 2015 levels in the absence of any measures. The already implemented controls, together with energy policies that promote less-polluting fuels in the household sector, will reduce the growth to 5 per cent, and an enforcement of all recent legislation should deliver a 10 per cent reduction in emissions compared with 2015 levels. Emissions could be cut by 75 per cent by 2030 with the full application of all available measures.

In contrast, population growth and dietary change will lead to greater agricultural production, especially of livestock, which will increase NH_3 emissions in the absence of policies stimulating and enforcing emission controls. In addition, persistent over-fertilization and strong reliance on urea and ammonium bicarbonate mineral fertilizers result in significant losses of nutrients and consequently NH_3 emissions to the atmosphere.

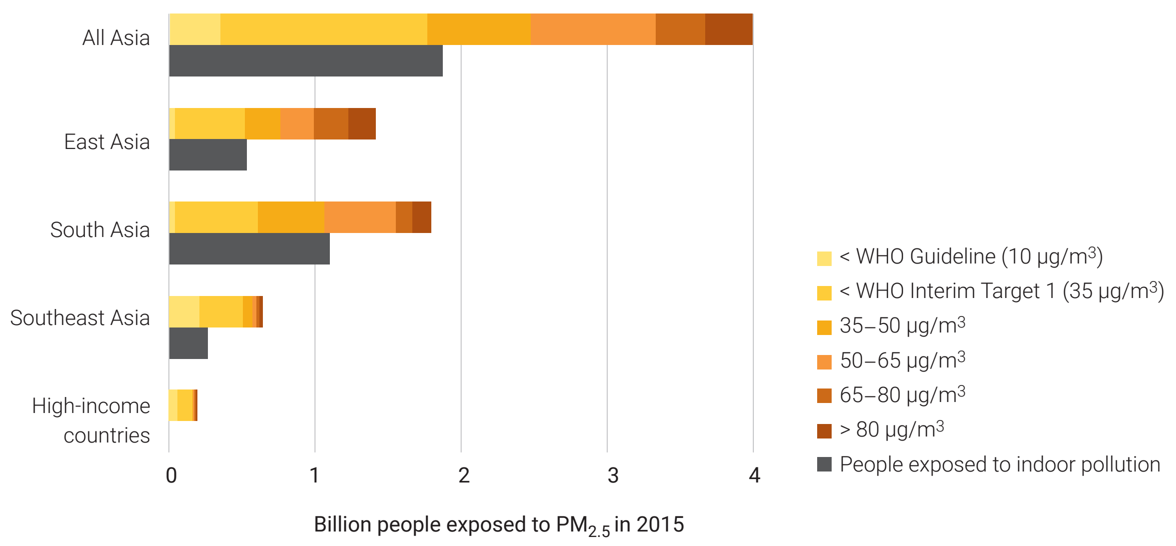


FIGURE 2.6: DISTRIBUTION OF POPULATION EXPOSURE TO AMBIENT $PM_{2.5}$ AND INDOOR POLLUTION IN 2015, ASIA-WIDE AND FOR THE MODELLED SUB-REGIONS

Source: GAINS 2017

Current policies will avoid a further deterioration in air quality at the large scale, but will not be sufficient to achieve air quality standards

Need to build on current policy

Asia's policy decisions are not only critical for controlling future emissions, but equally for the resulting air quality. Hypothetically, without any policy interventions, population-weighted mean exposure to $PM_{2.5}$ would grow by almost 50 per cent by 2030, from 43 µg/m³ in 2015 to about 62 µg/m³. This is a consequence of higher precursor emissions combined with continued urbanization trends, which will increase the share of the urban population in Asia.

The already implemented measures reduce the hypothetical growth by about 11 µg/m³ by 2030, and a further 9 µg/m³ reduction would result from an effective enforcement of all recently decided emission control legislation. Thereby, on average, current legislation will maintain population-weighted mean exposure at the current levels, and thereby compensate the impacts of the expected 80 per cent economic growth.

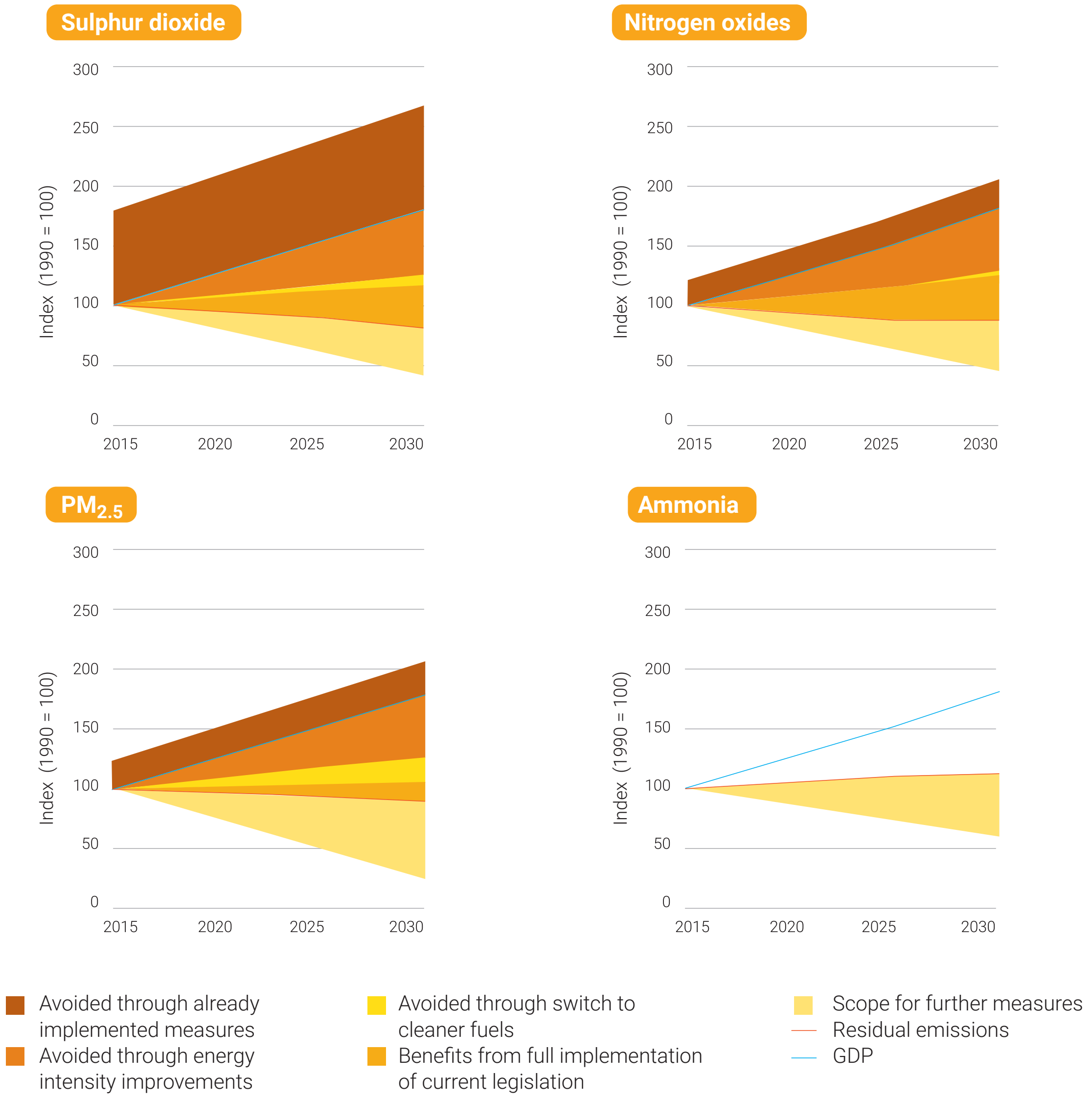


FIGURE 2.7: THE CONTRIBUTIONS OF DIFFERENT POLICY INTERVENTIONS TO THE DECOUPLING OF ECONOMIC GROWTH FROM EMISSIONS OF $PM_{2.5}$ AND ITS PRECURSORS UNDER CURRENT LEGISLATION UP TO 2030, FOLLOWING THE IEA WEO ENERGY SCENARIO, AND SCOPE FOR FURTHER EMISSION CONTROLS

However, current legislation will not be sufficient to improve air quality to such an extent that national and international air quality standards will be met. Despite some decline in ambient $PM_{2.5}$ in Eastern Asia, large exceedances of air quality standards will remain in heavily industrialized areas with high population densities (Figure 2.8). In Western Asia, ambient $PM_{2.5}$ levels would grow further under current legislation, adding to the high load from natural sources, particularly soil dust.

Some 2.4 billion people – 54 per cent of the population – will suffer from $PM_{2.5}$ levels above the highest WHO Interim Target, and 1.3 billion people will remain exposed to indoor pollution

Overall, limited improvements in air quality from current policies will not significantly reduce total population exposure to harmful $PM_{2.5}$ pollution compared to today. By 2030, still only 8 per cent of the Asian population, around 363 million people, will live with air quality that complies with the WHO Guideline. About 2.4 billion people, 54 per cent of the total population, will still face $PM_{2.5}$ levels in excess of the highest WHO Interim Target level 1 (35 µg/m^3). In addition, 1.3 billion people will remain exposed to indoor pollution (Figure 2.9).

2.3.4 The top 25 clean air measures for Asia

In total, more than 2,000 emission control options were considered in the analysis. Of these, 25 measures were identified that deliver the greatest benefits for human health from reduced exposure to ambient and indoor air pollution in Asia, while at the same time contributing to development priority goals. The full set of top 25 measures is grouped into three categories (Table 2.2).

Measures that are widely adopted in the current emission control legislation of Asian countries will avoid a further deterioration of air quality

The contribution of conventional measures

By now, many Asian countries have adopted – and partially implemented – effective measures to control air pollutant emissions, which in practice decouple economic growth from emission trends. Most of these measures focus on emission sources that exhibit rapid growth with increasing levels of economic activity, such as large combustion plants, industrial processes and mobile sources (Table 2.3).

Especially effective are post-combustion emission controls at large plants in the power and industrial sectors, emissions standards for

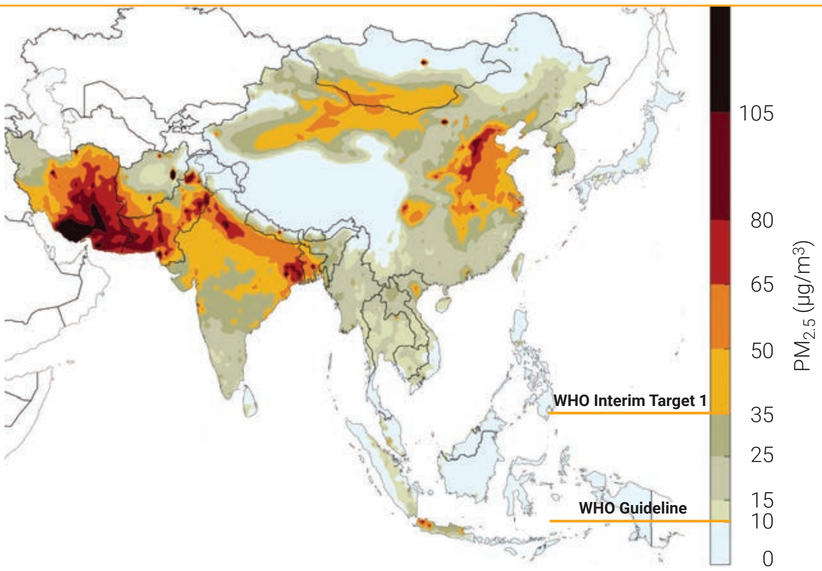


FIGURE 2.8: AMBIENT LEVELS OF $PM_{2.5}$ IN ASIA IN 2030 UNDER CURRENT LEGISLATION

Source: GAINS 2017

diesel and gasoline vehicles, and measures to control emissions from industrial processes (non-combustion), including steel, cement and glass production. In addition, where implemented, effective inspection and maintenance schemes for vehicles avoid substantial exposure (Figure 2.10).

The future benefits of these policies and measures depend on the effectiveness of their implementation. By 2030, currently implemented measures will realize about 40 per cent of their full potential, especially in East Asia and the high-income countries. Another 40 per cent will depend on timely implementation and effective enforcement of legislation that is already enshrined in law but not yet implemented, predominantly in South Asia.

Asia-wide application of conventional measures in countries that have not yet developed more advanced air quality control regimes can deliver additional improvements

Thus, by 2030, over all of Asia, the measures that are already implemented will reduce mean population exposure to $PM_{2.5}$ by about 11 $\mu g/m^3$ compared to a hypothetical no-control situation. Full and timely implementation of the policies that are already laid down in legislation but not yet in operation would deliver a further 9 $\mu g/m^3$ reduction, so that on average the mean population exposure would remain at today's level, compensating the impacts of the predicted 80 per cent economic growth.

An Asia-wide application of the conventional measures (Table 2.3) in countries that have not yet developed more advanced air quality control regimes, such as in Southeast Asia, and the extension of current laws to smaller industrial sources in other countries, for example in East Asia, can deliver additional air quality improvements and reduce population exposure by 8 $\mu g/m^3$, taking it down to about 35 $\mu g/m^3$.

However, this level of exposure still fails to conform to most national and international air quality standards, and large shares of the Asian population will remain exposed to pollution levels that exceed even the highest WHO Interim Target. Furthermore, such policies will not protect people exposed to indoorair pollution.

Any effective attempt to bring ambient air quality levels down to national and international standards must include further measures

Next-stage measures

Since the current measures offer only limited potential for fundamental improvements in today's air quality, any effective attempt to bring ambient

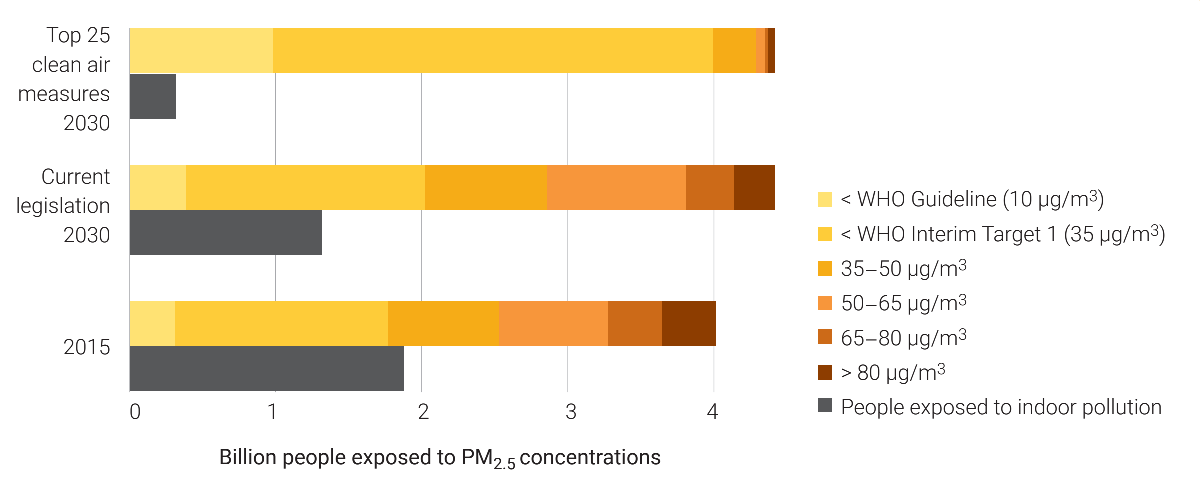


FIGURE 2.9: DISTRIBUTION OF POPULATION EXPOSURE TO $PM_{2.5}$, IN 2015 AND IN 2030 UNDER CURRENT LEGISLATION

air quality levels down to national and international standards must include measures in sectors that do not feature prominently in current plans. Today's Asian portfolios of policy measures mainly focus on emission sources that are growing rapidly with economic development, including large industrial and power plants and road transport, but address small and dispersed sources such as households, agriculture, waste burning and forest fires inadequately. More important in Asia than on other continents, these sectors produce considerable amounts of primary particulate

TABLE 2.2: THE TOP 25 CLEAN AIR MEASURES

Regional application of conventional measures

Post-combustion controls	Introduce state-of-the-art end-of-pipe measures to reduce SO_2, NO_x and particulate emissions at power stations and in large-scale industry
Industrial process emissions standards	Introduce advanced emissions standards in industries, e.g., iron and steel plants, cement factories, glass production, chemical industry, etc.
Emissions standards for road vehicles	Strengthen all emissions standards; special focus on regulation of light- and heavy-duty diesel vehicles
Vehicle inspection and maintenance	Enforce mandatory checks and repairs for vehicles
Dust control	Suppress construction and road dust; increase green areas

Next-stage air quality measures that are not yet major components of clean air policies in many parts of Asia and the Pacific

Agricultural crop residues	Manage agricultural residues, including strict enforcement of bans on open burning
Residential waste burning	Strictly enforce bans on open burning of household waste
Prevention of forest and peatland fires	Prevent forest and peatland fires through improved forest, land and water management and fire prevention strategies
Livestock manure management	Introduce covered storage and efficient application of manures; encourage anaerobic digestion
Nitrogen fertilizer application	Establish efficient application; for urea also use urease inhibitors and/or substitute with, for example, ammonium nitrate
Brick kilns	Improve efficiency and introduce emissions standards
International shipping	Require low-sulphur fuels and control of particulate emissions
Solvent use and refineries	Introduce low-solvent paints for industrial and do-it-yourself applications; leak detection; incineration and recovery

TABLE 2.2: THE TOP 25 CLEAN AIR MEASURES (contd.)

Measures contributing to development priority goals with benefits for air quality	
Clean cooking and heating	Use clean fuels – electricity, natural gas, liquefied petroleum gas (LPG) in cities, and LPG and advanced biomass cooking and heating stoves in rural areas; substitution of coal by briquettes
Renewables for power generation	Use incentives to foster extended use of wind, solar and hydro power for electricity generation and phase out the least efficient plants
Energy efficiency for households	Use incentives to improve the energy efficiency of household appliances, buildings, lighting, heating and cooling; encourage roof-top solar installations
Energy efficiency standards for industry	Introduce ambitious energy efficiency standards for industry
Electric vehicles	Promote the use of electric vehicles
Improved public transport	Encourage a shift from private passenger vehicles to public transport
Solid waste management	Encourage centralized waste collection with source separation and treatment, including gas utilization
Rice paddies	Encourage intermittent aeration of continuously flooded paddies
Wastewater treatment	Introduce well-managed two-stage treatment with biogas recovery
Coal mining	Encourage pre-mining recovery of coal mine gas
Oil and gas production	Encourage recovery of associated petroleum gas; stop routine flaring; improve leakage control
Hydrofluorocarbon (HFC) refrigerant replacement	Ensure full compliance with the Kigali Amendment

emissions ($PM_{2.5}$) as well as precursor gases such as NH_3 that contribute to and control the formation of secondary particles in the atmosphere.

Measures are available and proven that can reduce these emissions, including the more efficient use of fertilizers, prevention of forest and peat fires, a ban on open burning of agricultural residues and household waste, improved manure management, and control of solvent emissions in industry (Table 2.4).

A portfolio that includes these measures in addition to the conventional ones could reduce population exposure to $PM_{2.5}$ in Asia by a further 6 $\mu g/m^3$ (Figure 2.11), and thereby cut it by more than one third compared to 2015, or by more than half compared to the hypothetical situation without any emission controls in 2030. It should be mentioned that these measures, while not yet applied at large scale in Asia, are important elements of today's air quality management portfolios in other parts of the world, including Europe and North America.

TABLE 2.3: EMISSION CONTROLS THAT ARE PROVEN AND WIDELY APPLIED IN ASIA

Regional application of conventional measures

Post-combustion controls	Introduce state-of-the-art end-of-pipe measures to reduce SO_2, NO_x and particulate emissions at power stations and in large-scale industry
Industrial process emissions standards	Introduce advanced emissions standards in industries, e.g., iron and steel plants, cement factories, glass production, chemical industry, etc.
Emissions standards for road vehicles	Strengthen all emissions standards; special focus on regulation of light- and heavy-duty diesel vehicles
Vehicle inspection and maintenance	Enforce mandatory checks and repairs for vehicles
Dust control	Suppress construction and road dust; increase green areas

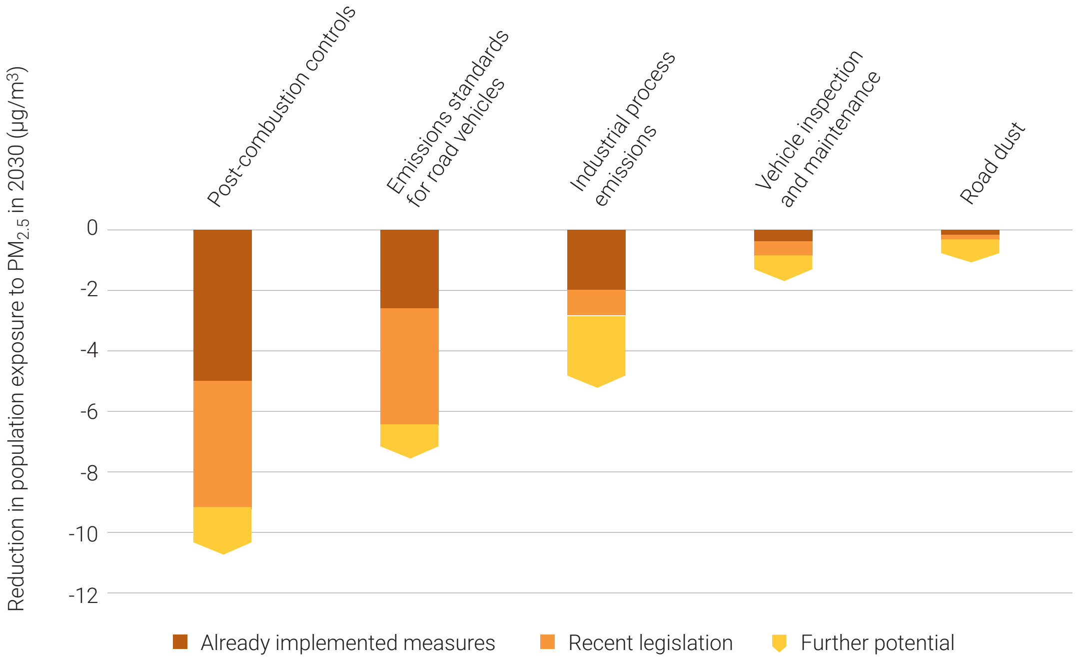


FIGURE 2.10: IMPACTS OF THE EMISSION CONTROL MEASURES THAT ARE NOW WIDELY APPLIED IN ASIA ON POPULATION-WEIGHTED MEAN EXPOSURE TO $PM_{2.5}$ IN 2030, RANKED BY TOTAL EXPOSURE REDUCTION

TABLE 2.4: NEXT-STAGE AIR QUALITY MEASURES TO REDUCE PARTICULATE AND PRECURSOR EMISSIONS

Next-stage air quality measures that are not yet major components of clean air policies in many parts of Asia and the Pacific	
Agricultural crop residues	Manage agricultural residues, including strict enforcement of bans on open burning
Residential waste burning	Strictly enforce bans on open burning of household waste
Prevention of forest and peatland fires	Prevent forest and peatland fires through improved forest, land and water management and fire prevention strategies
Livestock manure management	Introduce covered storage and efficient application of manures; encourage anaerobic digestion
Nitrogen fertilizer application	Establish efficient application; for urea also use urease inhibitors and/or substitute with, for example, ammonium nitrate
Brick kilns	Improve efficiency and introduce emissions standards
International shipping	Require low-sulphur fuels and control of particulate emissions
Solvent use and refineries	Introduce low-solvent paints for industrial and do-it-yourself applications; leak detection; incineration and recovery

Action aiming to contribute to development priorities can eliminate, or at least reduce, some of the most polluting activities

Development priorities and air quality

The portfolios of conventional and next-stage measures presented in Tables 2.3 and 2.4 have been compiled with a narrow focus on air quality. Typically, such measures can be decided by the authorities that are dealing with air quality management, involving other relevant stakeholders such as vehicle producers, power companies, refineries or industrial organizations. However, there are additional measures that offer further means of improving air quality, even if they do not primarily target air pollution. Often, they fall under the jurisdiction of different authorities and are discussed in different policy frameworks in which air quality managers are often not represented. These include, *inter alia*, measures closely related to economic and social development, energy or agricultural policies, or urban management. In particular, action aiming to contribute to the development priorities reflected in various SDGs can also eliminate, or at least reduce, some of the most polluting activities, bringing additional emission reductions that are usually beyond the immediate jurisdiction of environmental authorities. Relevant SDGs include, *inter alia*, SDG 6: Clean Water and Sanitation, SDG 7: Affordable and Clean Energy, SDG 11: Sustainable Cities and Communities, SDG 12: Responsible Consumption and Production, and SDG 13: Climate Action.

To this end, the analysis explored measures aimed at development priorities that affect the precursor emissions of $PM_{2.5}$ (Table 2.5), and whose potential impacts on activity levels have been quantified in the International Energy Agency (IEA) *World Energy Outlook Special Report: Energy and Air Pollution* (IEA WEO 2016).

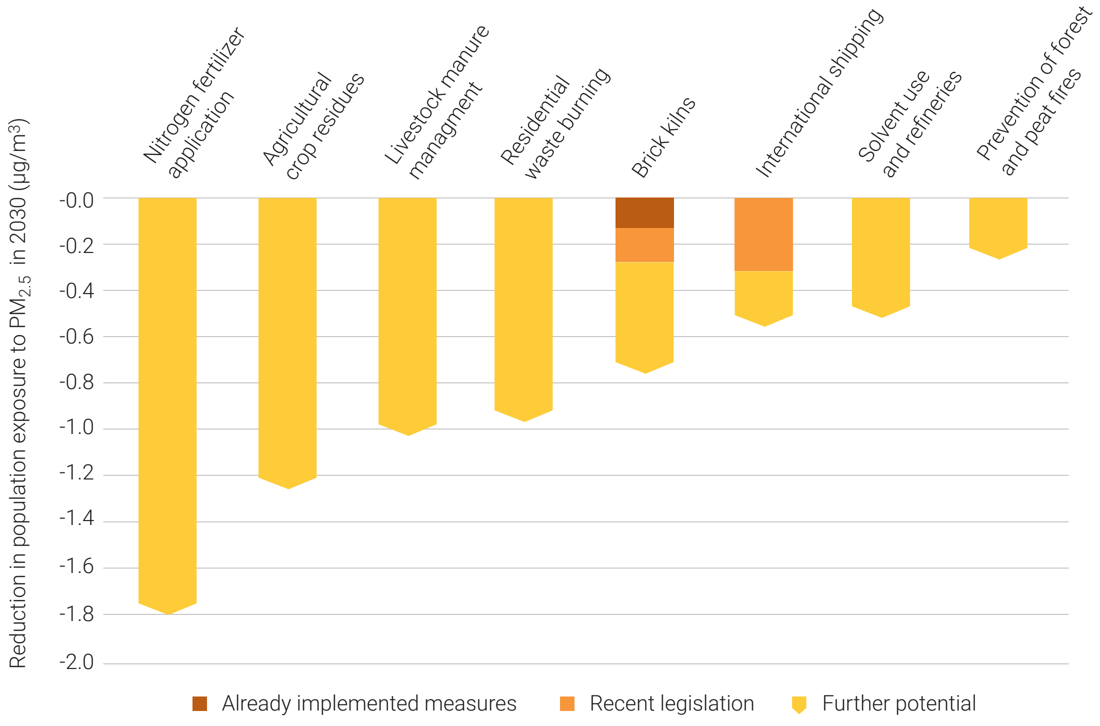


FIGURE 2.11: IMPACTS OF ASIA-SPECIFIC NEXT-STAGE AIR QUALITY MEASURES ON POPULATION-WEIGHTED EXPOSURE TO $PM_{2.5}$ IN 2030, RANKED BY TOTAL REDUCTION

TABLE 2.5: MEASURES AIMED AT DEVELOPMENT PRIORITIES THAT REDUCE $PM_{2.5}$ PRECURSOR EMISSIONS

Measures contributing to development priority goals with benefits for air quality	
Clean cooking and heating	Use clean fuels – electricity, natural gas, liquefied petroleum gas (LPG) in cities, and LPG and advanced biomass cooking and heating stoves in rural areas; substitution of coal by briquettes
Renewables for power generation	Use incentives to foster extended use of wind, solar and hydro power for electricity generation and phase out the least efficient plants
Energy efficiency for households	Use incentives to improve the energy efficiency of household appliances, buildings, lighting, heating and cooling; encourage roof-top solar installations
Energy efficiency standards for industry	Introduce ambitious energy efficiency standards for industry
Electric vehicles	Promote the use of electric vehicles
Improved public transport	Encourage a shift from private passenger vehicles to public transport

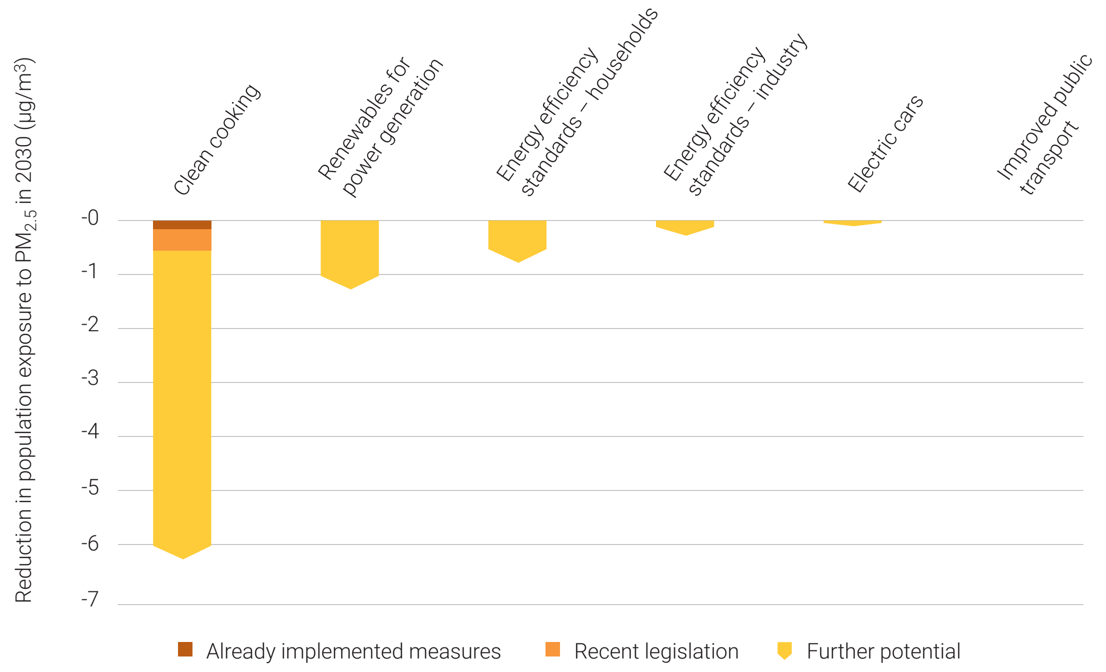


FIGURE 2.12: IMPACTS OF DEVELOPMENT PRIORITY MEASURES ON POPULATION-WEIGHTED EXPOSURE TO $PM_{2.5}$ IN 2030, RANKED BY TOTAL REDUCTION

Following the assumptions about implementation rates of the IEA WEO energy scenario, collectively these measures could reduce population-weighted mean exposure in Asia by another 8 μg/m^3 in 2030 (Figure 2.12), and correspondingly more thereafter, in addition to their primary benefits for development priorities.

Effective air quality management must also address the growing threat of ground-level ozone

The growing threat of ozone

Exposure to ground-level O_3 is the second largest risk factor for human health from ambient pollution, albeit current quantifications suggest much lower impacts than for $PM_{2.5}$. In addition, ground-level O_3 causes significant damage to vegetation, including agricultural crops.

By 2030, in the absence of appropriate policy interventions, population-weighted mean O_3 in ambient air in Asia would increase by about 50 per cent due to population growth, urbanization and economic development.

The measures in the conventional and next-stage portfolios were identified with a clear focus on $PM_{2.5}$ precursor emissions in ambient air (NO_x, VOCs, SO_2 and NH_3). At the same time, while targeted at $PM_{2.5}$, they also affect three out of the four precursor emissions of ground-level O_3, NO_x, VOCs and carbon monoxide (CO), reducing them by 50, 60 and 70 per cent, respectively, compared to the current legislation case (Table 2.6).

However, these measures will not affect methane (CH_4) emissions, another precursor to ground-level O_3. Methane has a strong impact on background O_3 levels at the hemispheric scale, which showed a marked increase in the last decades, and about 45 per cent of global CH_4 emissions occur in Asia[2].

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[2] For example, https://data.worldbank.org/indicator/EN.ATM.METH.KT.CE?view=chart

Thus, measures focused solely on $PM_{2.5}$ do not exploit the full mitigation potential for O_3 precursor emissions and might not be sufficient to bring down O_3 to levels that do not cause damage to human health, crops and ecosystems. In the interests of a comprehensive clean air strategy, this assessment also explores the additional benefit of extending the portfolio of measures to include low-cost options for mitigating CH_4 emissions.

A number of practical mitigation opportunities exist in Asia for CH_4 emissions (Table 2.7). While the inclusion of these measures in a comprehensive air quality management portfolio is justified by concerns about ground-level O_3, it should be mentioned that a reduction in CH_4 emissions also forms an integral part of SDG 13: Climate Action.

TABLE 2.6: KEY MEASURES CONTRIBUTING TO GROUND-LEVEL OZONE MITIGATION

Regional application of conventional measures	
Post-combustion controls	Introduce state-of-the-art end-of-pipe measures to reduce SO_2, NO_x and particulate emissions at power stations and in large-scale industry
Emissions standards for road vehicles	Strengthen all emissions standards; special focus on regulation of light- and heavy-duty diesel vehicles
Vehicle inspection and maintenance	Enforce mandatory checks and repairs for vehicles
Next-stage air quality measures that are not yet major components of clean air policies in many parts of Asia and the Pacific	
Solvent use and refineries	Introduce low-solvent paints for industrial and do-it-yourself applications; leak detection; incineration and recovery

TABLE 2.7: ADDITIONAL MEASURES AIMED AT GROUND-LEVEL OZONE WITH CO-BENEFITS FOR SUSTAINABLE DEVELOPMENT

Measures contributing to development priority goals with benefits for air quality	
Solid waste management	Encourage centralized waste collection with source separation and treatment, including gas utilization
Rice paddies	Encourage intermittent aeration of continuously flooded paddies
Wastewater treatment	Introduce well managed two-stage treatment with biogas recovery
Coal mining	Encourage pre-mining recovery of coal mine gas
Oil and gas production	Encourage recovery of associated petroleum gas; stop routine flaring; leakage control

Hydrofluorocarbon management

One final measure contributing to sustainable development is the replacement of hydrofluorocarbon (HFC) refrigerants with environmentally friendly alternatives through full ratification and compliance with the Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (Table 2.8).

Hydrofluorocarbons are a group of powerful manufactured greenhouse gases used primarily as replacements for ozone-depleting substances currently being phased out under the Montreal Protocol, and are the fastest-growing group of greenhouse gases in many countries due in part to rapidly growing consumer refrigeration and air conditioning markets. In addition to its direct benefits, HFC mitigation can also catalyse improvements in the energy efficiency of the refrigerators, air conditioners and other products and equipment that use HFC refrigerants, which is a critical part of SDG 7: Affordable and Clean Energy.

Implementation of the top 25 clean air measures for Asia will achieve significant improvements in air quality

Reductions in population exposure

Implementation of the top 25 clean air measures for Asia (Table 2.2) could bring mean population exposure to $PM_{2.5}$ down to about 20 µg/m^3 in 2030 (Figure 2.13).

Overall, measures that are already widely applied in Asia – especially post-combustion emission controls in power plants and industry as well as for road transport – offer the largest improvements. Beyond these, key measures include access to clean cooking fuels, enhanced use of renewable energy, control of forest fires and improved agricultural practices (Figure 2.14).

Achieving air quality standards

Implementation of the top 25 clean air measures could deliver, in 2030, air quality that conforms to current national air quality criteria over large areas of Asia, but not everywhere. In particular, they will not be sufficient in some megacities surrounded by industrial areas, such as Beijing or Delhi, although even there additional local measures are likely to bring the standards within reach. In addition, $PM_{2.5}$ levels will remain high in regions that are heavily influenced by soil dust (Figure 2.15).

However, and most importantly, 1 billion people – 22 per cent of the Asian population – will enjoy air quality in line with the WHO Guideline, compared to less than 8 per cent in 2015. Furthermore, the number of people exposed to pollution above the highest WHO Interim Target level will decline by 80 per cent, from 2.3 billion in 2015 – 55 per cent of the Asian population – to 430 million people, leaving only 10 per cent exposed to such pollution levels (Figure 2.16).

TABLE 2.8: MEASURES WITH ADDITIONAL BENEFITS

Measures contributing to development priority goals with benefits for air quality	
Hydrofluorocarbon (HFC) refrigerant replacement	Ensure full compliance with the Kigali Amendment

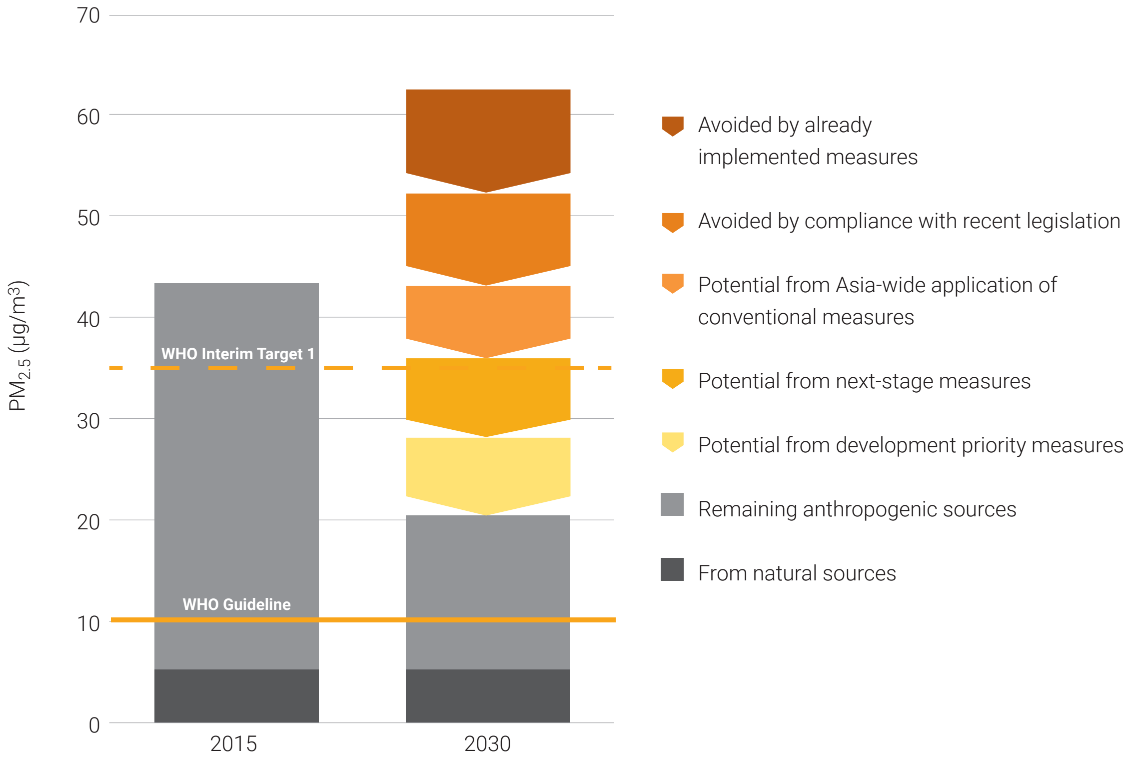


FIGURE 2.13: CONTRIBUTIONS TO REDUCTIONS IN POPULATION-WEIGHTED MEAN EXPOSURE TO $PM_{2.5}$, 2015 AND 2030

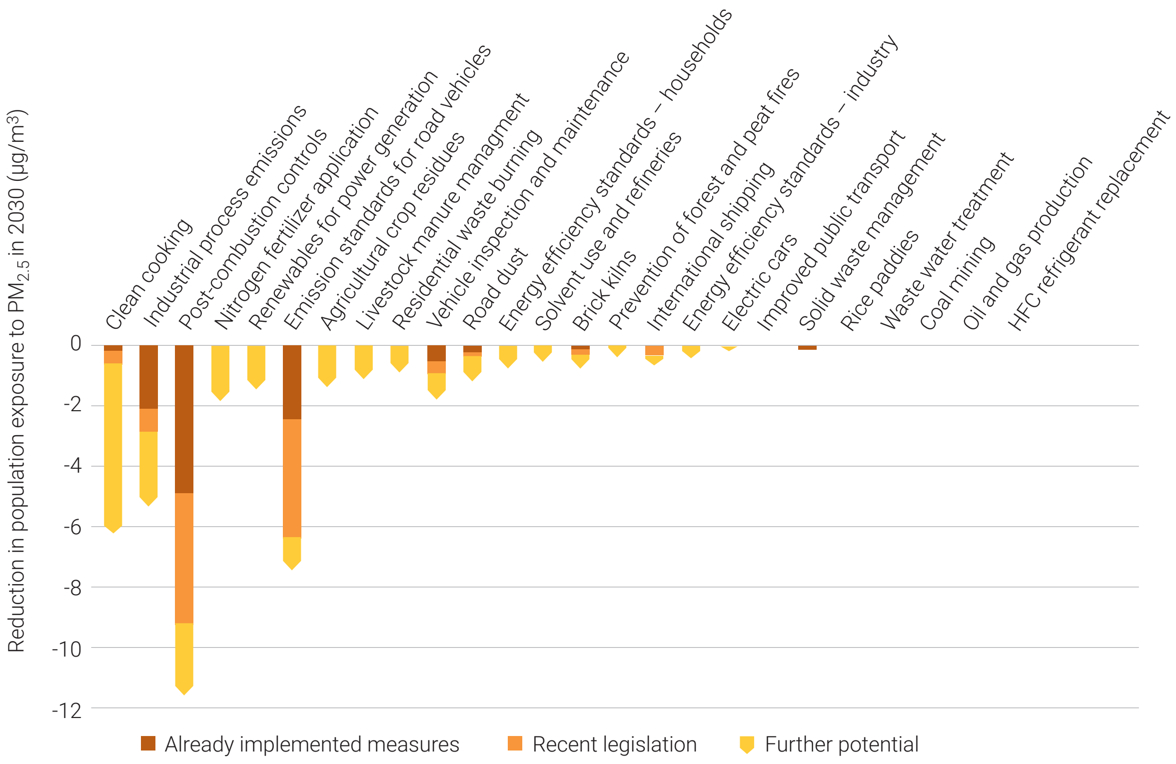


FIGURE 2.14: IMPACTS ON POPULATION-WEIGHTED EXPOSURE TO $PM_{2.5}$ IN 2030 OF 25 CLEAN AIR MEASURES FOR ASIA, RANKED BY FURTHER POTENTIAL

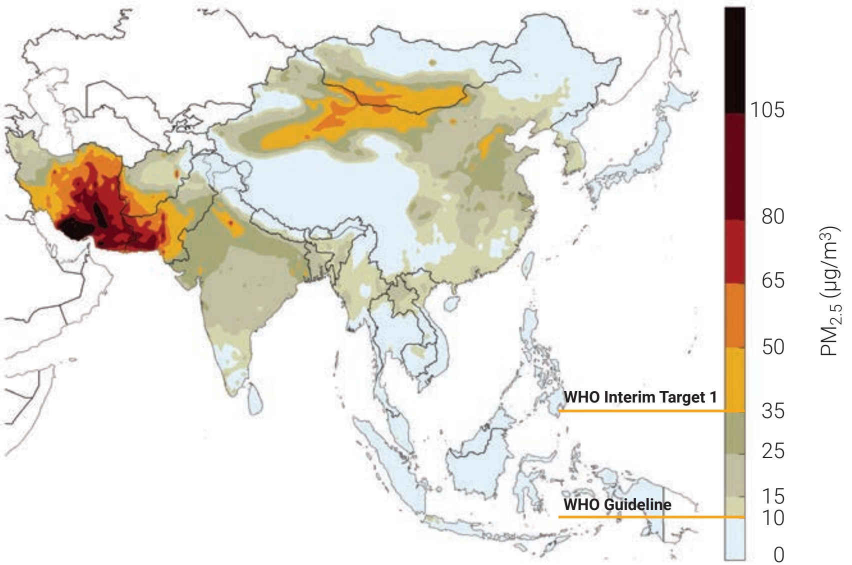


FIGURE 2.15: PM$_{2.5}$ CONCENTRATIONS IN ASIA IN 2030 AFTER IMPLEMENTATION OF THE TOP 25 CLEAN AIR MEASURES

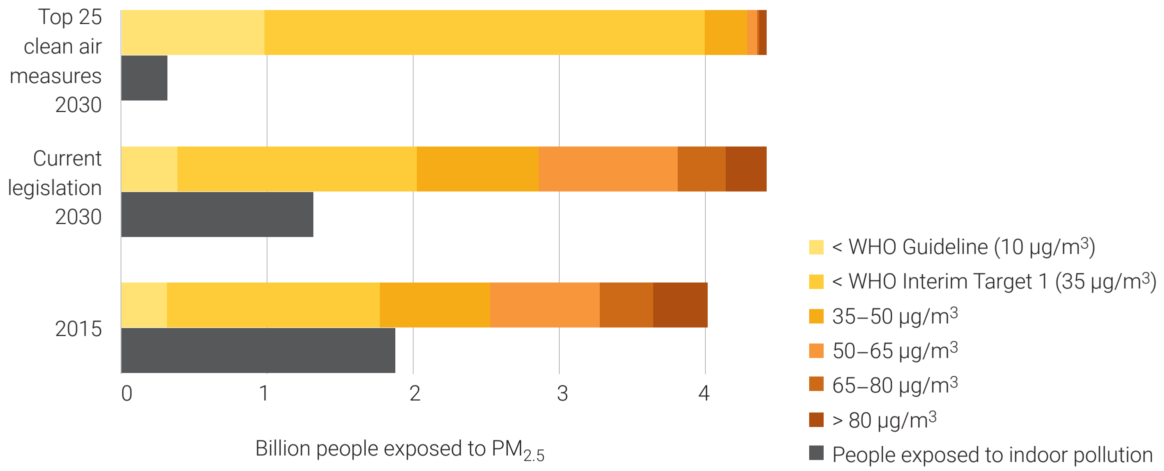


FIGURE 2.16: POPULATION EXPOSURE TO PM$_{2.5}$ IN 2015 AND IN 2030 FOR THE DIFFERENT POLICY SCENARIOS

The 25 measures will provide clean air to 1 billion people and reduce the number facing exposure above the highest WHO Interim Target by 80 per cent

2.3.5 Health and other development benefits

The top 25 clean air measures for Asia identified in this chapter not only improve air quality and reduce human exposure to air pollution, they also benefit multiple sustainable development goals, including the mitigation of climate forcers (Figure 2.17).

The measures represent a package of concrete actions that simultaneously contribute to multiple outcomes relevant to national development priorities and their related SDGs, examples of which are described in greater detail in Chapter 3.

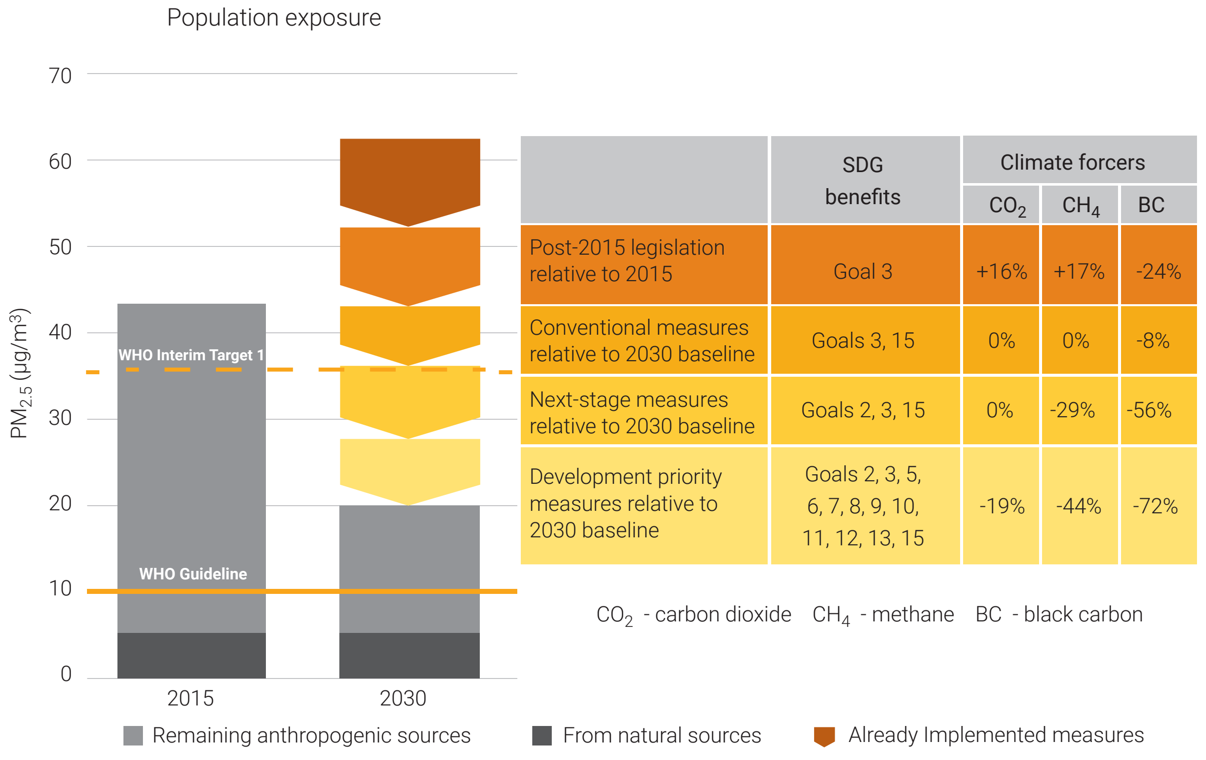
The portfolios of conventional and next-stage control measures are typically implemented for reasons of air quality, but also support other national development objectives. Conversely, the portfolio of measures aimed at national development priorities,such as ensuring access to affordable and clean energy (SDG 7), may not target air quality *per se*, but do contribute to improving it.

While no single SDG focuses on air quality specifically, it is addressed in the targets of three of them:

- SDG 3.9: to substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination;
- SDG 11.6: by 2030, reduce the adverse per person environmental impacts of cities, including by paying special attention to air quality, municipal and other waste management; and
- SDG 12.4: by 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment.

Avoidance of premature deaths

Based on identical patterns of population exposure to $PM_{2.5}$, two different parametrizations of the health impact assessment methodology applied in the 2010 and 2013 Global Burden of Disease studies result, respectively, in 3.1 and 1.9 million cases of premature death in 2015. In the current legislation baseline scenario, the health burden would increase to 4.0 and 2.5 million cases by 2030, despite the slight downwards trend in population exposure. This divergence is caused by (a) the population growth that is expected for this period, and (b) population



	SDG benefits	Climate forcers		
		CO_2	CH_4	BC
Post-2015 legislation relative to 2015	Goal 3	+16%	+17%	-24%
Conventional measures relative to 2030 baseline	Goals 3, 15	0%	0%	-8%
Next-stage measures relative to 2030 baseline	Goals 2, 3, 15	0%	-29%	-56%
Development priority measures relative to 2030 baseline	Goals 2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15	-19%	-44%	-72%

CO_2 - carbon dioxide CH_4 - methane BC - black carbon

FIGURE 2.17: IMPACTS OF THE TOP 25 CLEAN AIR MEASURES ON POPULATION EXPOSURE TO $PM_{2.5}$, EMISSIONS OF CLIMATE FORCERS, AND OTHER SDG BENEFITS

aging, which will increase the number of old people who are more susceptible to air pollution.

The top 25 clean air measures for Asia could lead to a 56 per cent lower $PM_{2.5}$ exposure in 2030 than in 2015. Premature mortality would then decline by 31–37 per cent, depending on the parametrization of the health impact assessment method. Due to the assumption of a flattening of the exposure-response curve at high $PM_{2.5}$ concentrations, health impacts decline at a lower rate than exposure.

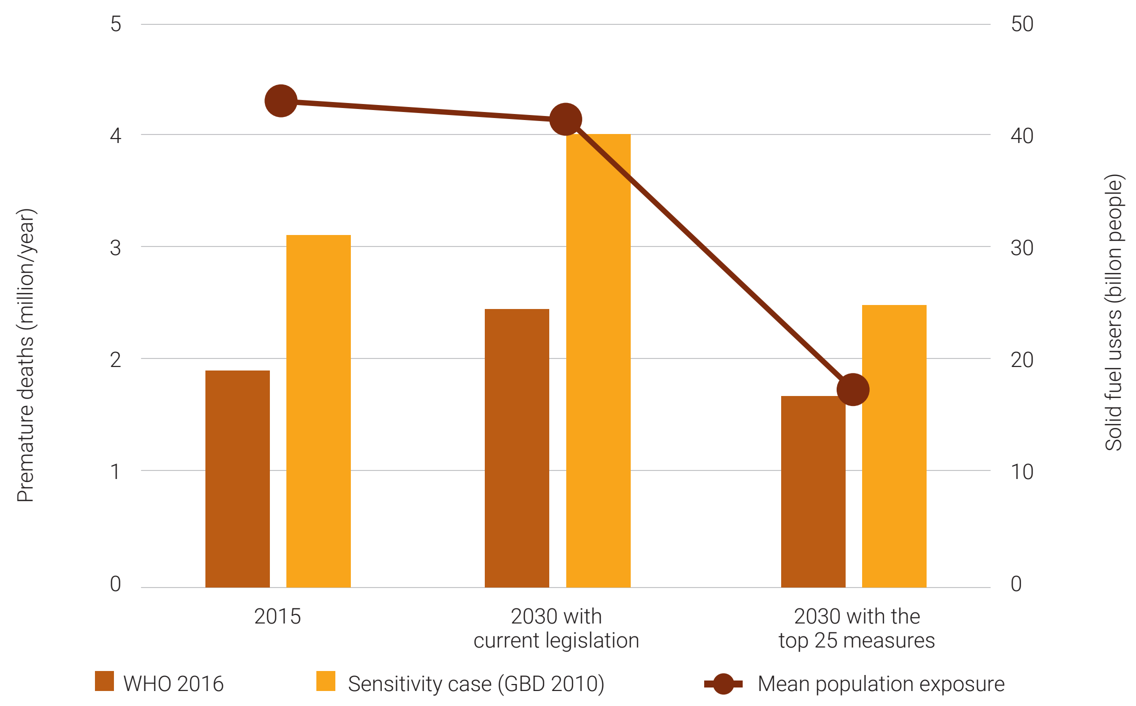
In addition, the top 25 clean air measures for Asia will also lead to a drastic reduction in the number of people using solid fuels (biomass and coal) for cooking purposes, from about 1.7 billion people in 2015 to fewer than 0.4 billion people in 2030. This scenario assumes that while access to clean cooking fuel will not be fully achieved throughout Asia by 2030, the remaining population in rural areas will use advanced biomass cookstoves or replace coal with briquettes.

This transition would cut the estimated number of premature deaths attributable to indoor pollution by 1.2–2.0 million cases per year, depending on the parametrization assumed for the health impact calculations (Figure 2.19).

Ozone-associated health impacts

The top 25 clean air measures for Asia also deliver substantial reductions in emissions of the O_3 precursor pollutants, NO_x, VOCs, CO and CH_4.

Using O_3 concentrations from two global atmospheric chemistry-transport models, and applying a health impact methodology used previously to quantify O_3 health impacts globally (Cohen *et al*. 2017; Anenberg *et al*. 2010), it was estimated that 331,000 premature deaths from



Note: The WHO 2016 parametrization follows WHO GBD 2016; the sensitivity case draws on Burnett *et al.* (2014), which is based on the GBD 2010 study.

FIGURE 2.18: PREMATURE DEATHS FROM EXPOSURE TO AMBIENT $PM_{2.5}$, ESTIMATED WITH DIFFERENT PARAMETRIZATIONS OF THE EXPOSURE-RESPONSE FUNCTIONS

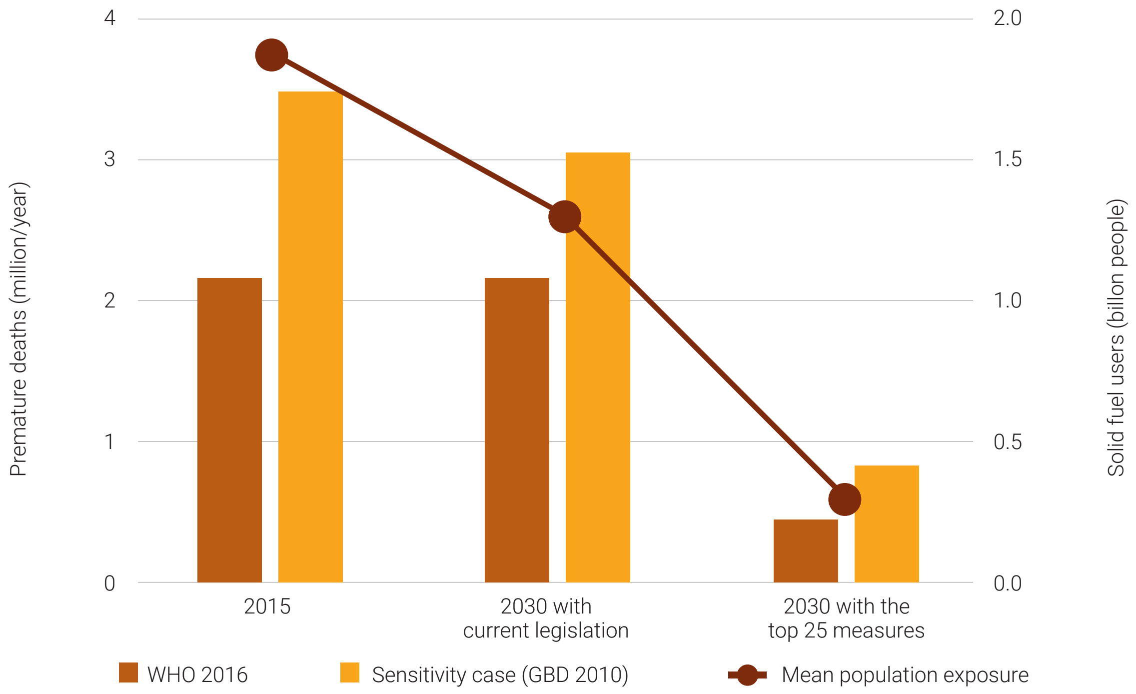
Source: GAINS 2017

respiratory diseases were associated with O_3 exposure in 2015 across Asia. The largest burden was in South Asia, followed by East and Southeast Asia and the High-income countries (Figure 2.20). Under current emission control legislation, the estimated O_3 health burden increases in all regions by 2030, driven by a larger and older population as well as changes in O_3 concentrations. The top 25 clean air measures for Asia reduce this estimated health burden by 40 per cent across Asia compared to the 2030 current legislation projection. The reduction in estimated O_3 health impacts in 2030 under full implementation of the 25 measures is largest in Southeast Asia, at 58 per cent relative to the 2030 current legislation scenario, followed by the High-income countries (44 per cent), East Asia (36 per cent) and South Asia (30 per cent). These benefits are driven largely by reductionsin NO_x and VOCs as well as additional reductions in background O_3 from CH_4 mitigation.

Despite uncertainties in quantifying O_3 health impacts due to relatively few studies in Asia, and recent evidence in the United States of America suggesting larger health effects than previously reported (Turner *et al*. 2016), the implementation of measures focused on reducing $PM_{2.5}$ concentrations, in combination with measures to reduce CH_4, would likely result in additional health benefits through reductions in O_3 exposure.

Ozone-associated crop loss

In addition to the impacts of air pollution on human health, ambient O_3 concentrations can also damage vegetation. This includes agricultural crops, resulting in reduced crop yields (Ainsworth *et al*. 2012; Feng and Kobayashi 2009), as well as damage to natural vegetation such as forests and grasslands (Wittig *et al*. 2009). Applying a methodology used previously to estimate O_3-induced crop yield loss globally.



Note: The WHO 2016 parametrization follows WHO GBD 2016; the sensitivity case draws on Burnett *et al*. (2014), which is based on the GBD 2010 study.

FIGURE 2.19: PREMATURE DEATHS FROM EXPOSURE TO INDOOR $PM_{2.5}$ POLLUTION, ESTIMATED WITH DIFFERENT PARAMETRIZATIONS OF THE EXPOSURE-RESPONSE FUNCTIONS

Source: GAINS 2017

(Van Dingenen *et al*. 2009), crop loss resulting from elevated O_3 concentrations was estimated to reduce yields of maize, rice, soy and wheat across Asia by 10 per cent, 4 per cent, 22 per cent and 9 per cent, respectively, in 2015. This is equivalent to a reduction in crop yield of 51 million tonnes across all four crops, the majority of which is rice and wheat loss. Only impacts due to elevated concentrations of O_3 are considered in this analysis; meteorological factors and the impact of climate change or changes in particulate matter are not included.

Implementation of the top 25 clean air measures for Asia would reduce estimated O_3-induced crop loss by an average of 45 per cent compared to the 2030 current legislation projection, equivalent to 20 million tonnes. The largest reductions would occur in Southeast Asia (56 per cent reduction in O_3-induced crop loss), followed by East Asia (48 per cent), modelled High-income countries (46 per cent), and South Asia (38 per cent). Estimating O_3 crop impacts is uncertain due to differences in crop responses between Asia and other regions (Emberson *et al*. 2009), and because these estimates do not include the impacts of O_3 on all crops, or its impacts on forests and other natural vegetation. However, the implementation of measures focused on reducing $PM_{2.5}$ concentrations, as well as measures targeting CH_4 emissions, are also likely to result in substantial co-benefits to agricultural crop yields through reductions in O_3 concentrations.

Climate and temperature

While this report analyses policy measures from the perspective of protecting human health by providing good air quality, the emission reductions that emerge from the top 25 clean air measures for Asia will also affect climate change in various

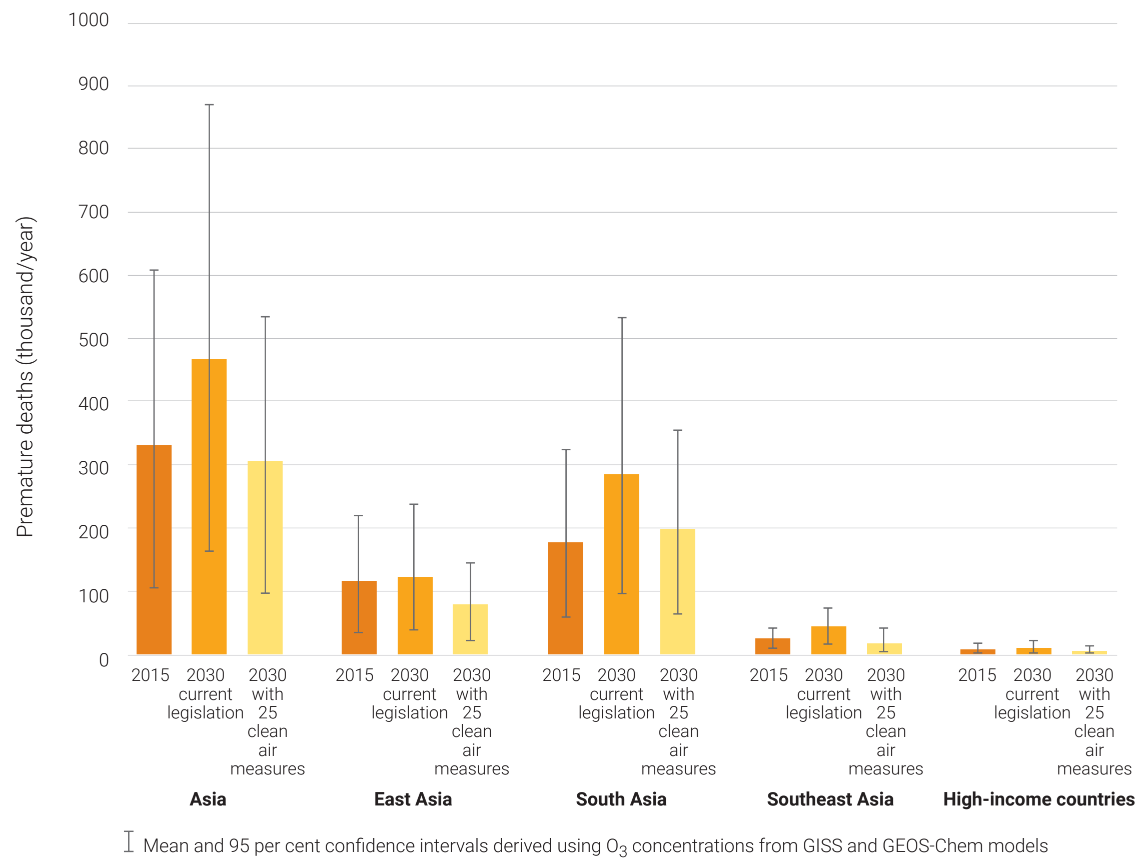


FIGURE 2.20: ESTIMATED NUMBER OF PREMATURE DEATHS ASSOCIATED WITH EXPOSURE TO O_3 IN 2015 AND IN 2030 UNDERCURRENT LEGISLATION, AND WITH THE TOP 25 CLEAN AIR MEASURES, ASIA-WIDE AND FOR THE MODELLED SUB-REGIONS

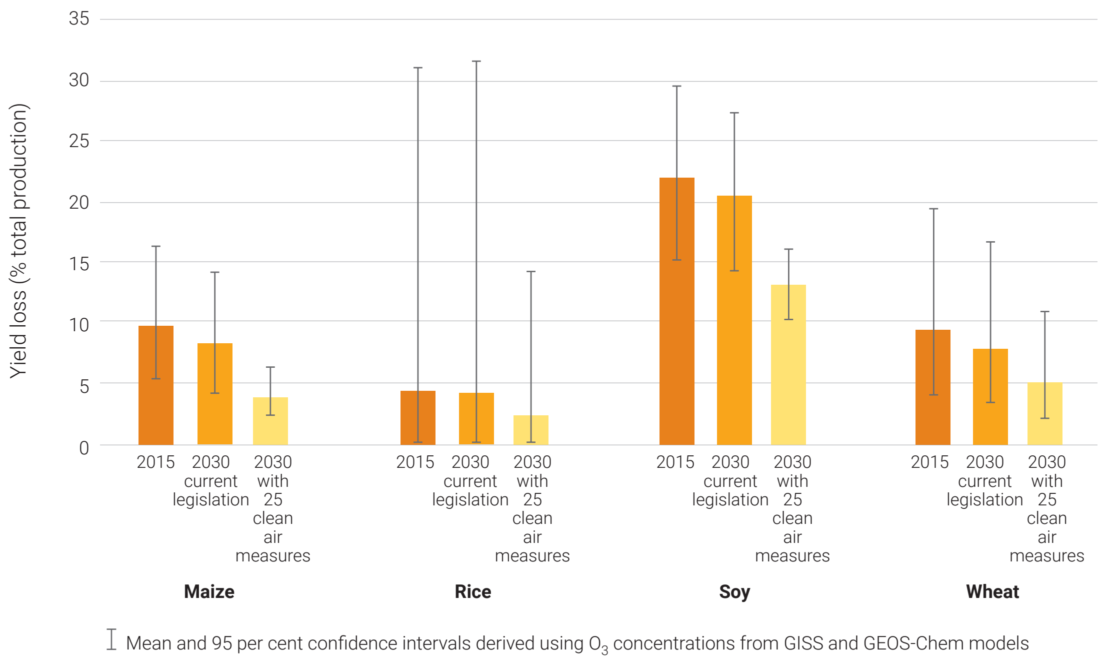
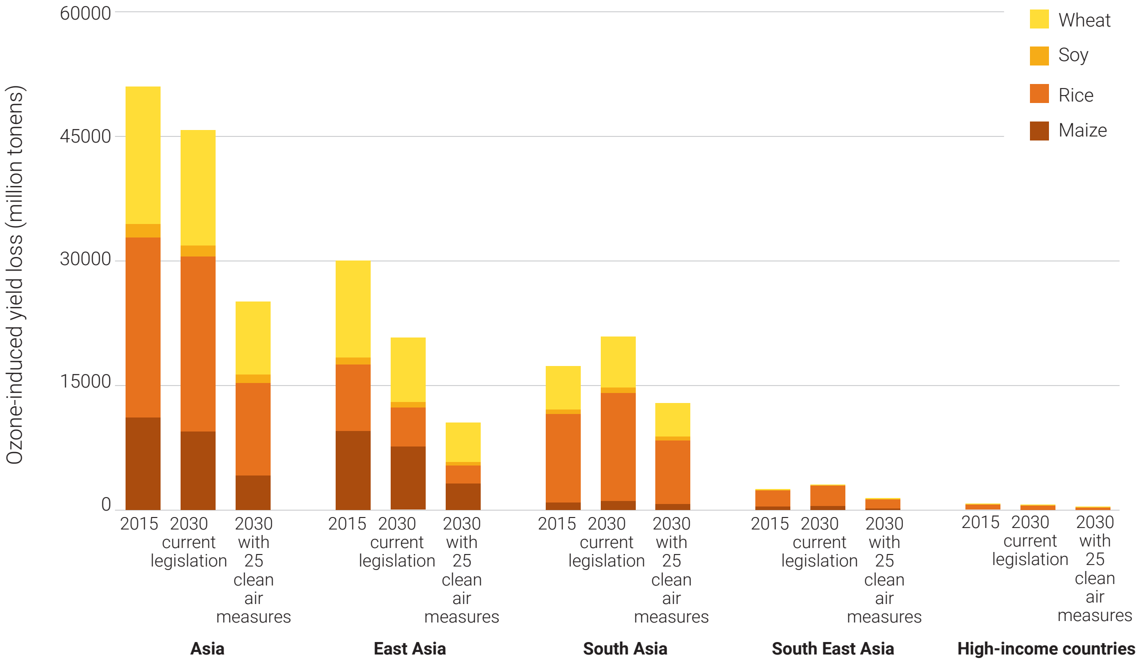


FIGURE 2.21: ESTIMATED O_3-INDUCED CROP LOSS IN 2015 AND IN 2030 UNDER CURRENT LEGISLATION, AND WITH THE TOP 25 CLEAN AIR MEASURES FOR ASIA, EXPRESSED AS A PERCENTAGE OF TOTAL CROP PRODUCTION



Note: Mean estimates derived using O_3 concentrations from GISS and GEOS-Chem models.

FIGURE 2.22: ESTIMATED O_3-INDUCED CROP LOSS IN 2015 AND IN 2030 UNDER CURRENT LEGISLATION AND WITH THE TOP 25 CLEAN AIR MEASURES, EXPRESSED AS TONNES OF CROP LOSS FOR FOUR STAPLE CROPS, ASIA-WIDE AND FOR THE MODELLED SUB-REGIONS

ways. Air pollutants, such as certain aerosols that constitute $PM_{2.5}$ as well as ground-level O_3, affect the radiative balance and influence temperature increase, especially in the near and medium terms. Different substances act in different ways: some are warming (BC, CH_4, CO), while others are cooling (SO_2, NO_x), with regional impacts on temperature as well as on the transport of heat over long distances – such as to the Himalayas and the Arctic.

The measures will provide a net reduction in the rate of global temperature increase and significantly contribute to a more sustainable lower rate of warming

The analysis clearly demonstrates that any meaningful move towards national and international air quality standards in Asia must involve substantial reductions in the precursor emissions of secondary $PM_{2.5}$, (SO_2, NO_x, NH_3 and VOCs). As, in general, these substances act as cooling agents, the reductions imply an increase in temperature due to the reduced cooling effect. However, it is also clear that the portfolios of emission control measures also affect emissions with opposite features – those that contribute to a temperature increase.

Off-line calculations of the impact of Asian emissions scenarios on global mean temperature using the absolute global temperature potential (AGTP) (Annex 2.1) method suggest that the changes in global emissions will result in an increase in global mean temperature of about 0.6°C by 2050 relative to 2015. The top 25 clean air measures applied in Asia could decrease this warming by about 0.31°C[3] (Figure 2.23).

This net temperature change emerges from several factors. By 2050, controls on the air pollutants SO_2, NO_x, NH_3, organic carbon (OC) and CO (but excluding BC) will cause a warming of 0.12°C (0.03–0.21). This is more than offset, however, by lower emissions of the short-lived climate pollutants (SLCPs) CH_4 and BC, reducing warming by 0.26°C (0.10–0.45), in addition to the 0.04°C reduction in warming from implementation of the Kigali Amendment by Asian countries. Furthermore, the lower CO_2 emissions that emerge from the top 25 measures will reduce temperature increase by 0.13°C(0.09–0.20). By providing a net reduction in the rate of global temperature increase, the top 25 clean air measures will significantly contribute to the Paris Agreement target of a more sustainable lower rate of warming.

A comparison with the portfolios of conventional and next-stage measures alone clearly highlights that the full set of top 25 clean air measures, including the development measures, not only results in larger health improvements, but at the same time decelerates temperature increase. Both alternative sets, which do not emphasize measures to reduce CO_2 and CH_4 emissions, have little net impact on temperature change, as the reductions in warming substances (BC) just balance the cuts in cooling agents (SO_2, NO_x and OC).

Following the different implementation timelines for the mitigation of the various climate forcers as well as their delayed impacts on temperature responses, the relative effects of the forcing substances varies over time. While at the beginning of the time horizon the SLCPs deliver the largest share (compensating the warming effects of the reduction in air pollutants), the accompanying mitigation of CO_2 emissions gains importance in the longer term (Figure 2.24).

While there are clear impacts on global mean temperature, emission changes in Asia will also affect temperature increase and precipitation within Asia, although these changes are not uniform across the region, nor are they all in the same direction (Figure 2.25). Calculations with the GISS Global Climate Model (Annex 2.1) indicate particularly significant changes in the 'Third Pole' area – the Himalayan and Tibetan Plateau. Furthermore, there is substantial cooling in the high-albedo regions of western parts of Asia, including parts of Afghanistan, Iran and Pakistan. Other parts of Asia show increases, decreases or no change, but these are not significant. This is not unusual for the highly industrialized coal-using regions, where there are significant sulphur (S) and NO_x emissions and a large reduction in those emissions in the mitigation strategy that leads to local cooling.

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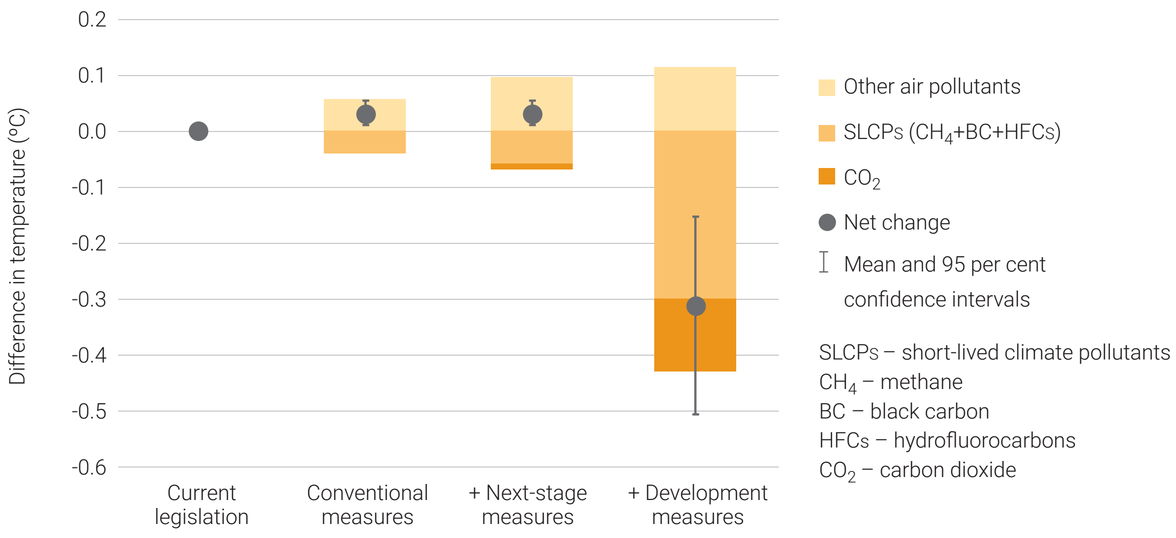
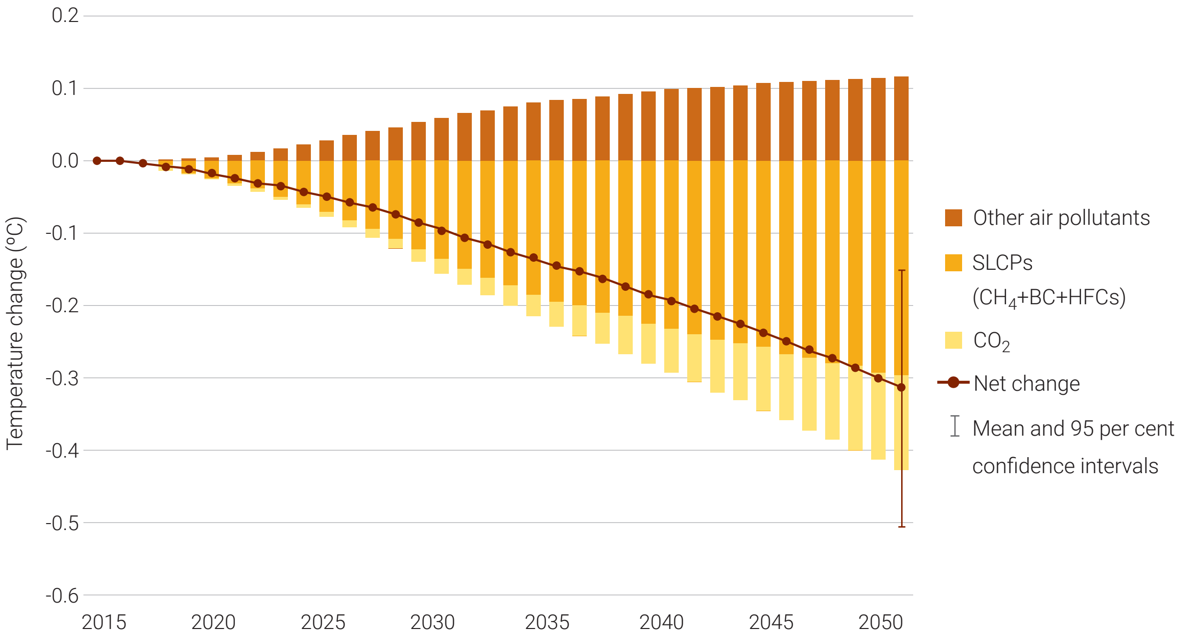
[3] 0.15–0.51 confidence interval for 67 per cent here and hereafter based on climate sensitivity and forcing uncertainties



Note: Other air pollutants include SO_2, NO_x, NH_3, OC and CO.

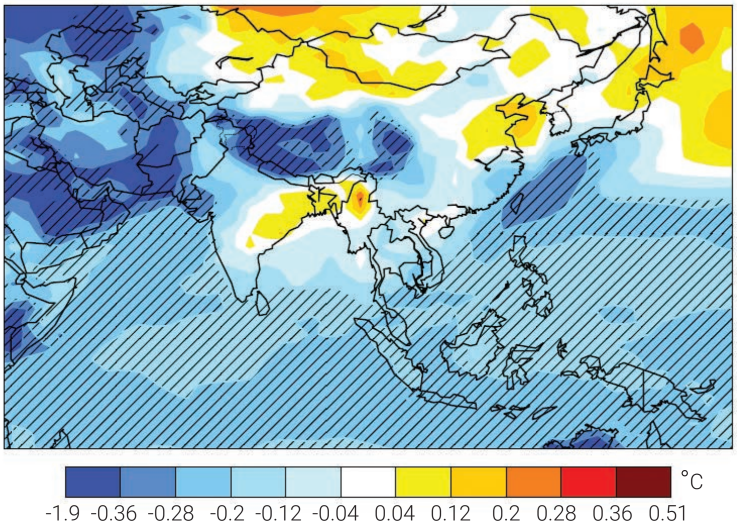
FIGURE 2.23: CHANGES IN GLOBAL MEAN TEMPERATURE IN 2050 FROM THE THREE PORTFOLIOS OF MEASURES RELATIVE TO THE CURRENT LEGISLATION BASELINE PROJECTION



SLCPs – short-lived climate pollutants; CH_4 – methane BC – black carbon HFCs – hydrofluorocarbons
CO_2 – carbon dioxide CO - carbon monoxide

Note: Other air pollutants include SO_2, NO_x, NH_3, OC and CO.

FIGURE 2.24: IMPACT OF THE DIFFERENT CLIMATE FORCERS ON GLOBAL MEAN TEMPERATURE RESULTING FROM IMPLEMENTATION OF THE TOP 25 CLEAN AIR MEASURES, COMPARED TO THE CURRENT LEGISLATION BASELINE, 2015–2050



Note: The stripes indicate significant changes (95 per cent confidence).

FIGURE 2.25: ANNUAL AVERAGE TEMPERATURE CHANGE UNDER THE TOP 25 MEASURES RELATIVE TO THE CURRENT LEGISLATION BASELINE FOR THE YEARS 2046–2054

Source: GISS model, 2017

2.3.6. Implementation costs

The GAINS model estimates life-cycle costs for emission reductions, adopting a social planner's perspective focusing on the diversion of societal resources, excluding transfer payments such as taxes, subsidies and profits, and balancing up-front investments with subsequent cost savings, for example from lower energy use.

With such a perspective, it is estimated that Asia currently spends about 1 per cent of its GDP (US$ 160 billion per year) on emission controls, with significant – although often hidden – benefits for air quality and human well-being. By 2030, while compensating for the additional pollution that will come from the 80 per cent enlarged economic activity, full implementation of current legislation will increase pollution control costs to 1.2 per cent of GDP. Full application of conventional air quality measures across Asia would require emission control costs of 1.55 per cent of GDP (Figure 2.26), and would reduce population exposure by one third. At costs of 1.85 per cent of GDP (about US$ 500 billion per year), inclusion of the next-stage measures could reduce population exposure by half.

While contributing to wealth and well-being, implementation of the top 25 clean air measures for Asia requires only a small share of the resources gained by future economic growth

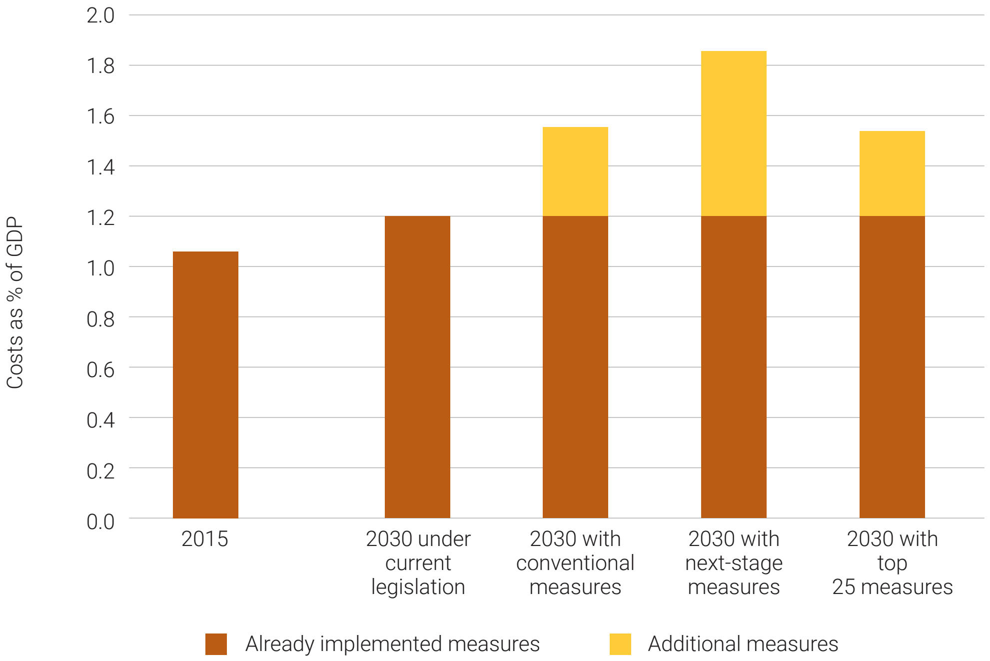
The full set of top 25 clean air measures for Asia would cut population exposure by 60 per cent. However, associated costs for air pollution controls decline to approximately 1.5 per cent of GDP, due to the lower consumption of polluting fuels reducing the requirement for pollution control equipment. Additional costs for implementing the measures that are primarily targeted at development priorities are outside the scope of this air pollution-centred assessment; however, it can be stated that the full package of 25 measures would save about US$ 75 billion per year on air pollution controls in addition to delivering substantial air quality benefits. Although air pollution control costs for all of Asia may seem high in absolute terms, at US$ 300–600 billion per year in 2030, they constitute a rather small share of about 5 per cent of the US$ 12 trillion per year increase in GDP envisaged for Asia by 2030. Presently, the largest share of pollution control costs is spent on technically advanced emission controls for vehicles, and this share is expected to grow further along with the increasing car fleet (Figure 2.27). Extension of the conventional pollution controls across all of Asia would double costs in the power and industrial sectors. The next-stage measures would direct additional pollution controls to the residential and agricultural sectors, although the cost shares of these sectors would remain small in the overall context, as many measures can be implemented at low cost.

However, while the societal costs of some measures are low, economic actors (companies or households) might face high up-front investments that will not be recovered within the short pay-back perspective of the private consumer, in contrast to the longer time horizon that is suitable for social planning purposes. Thereby, even if the societal costs of some next-stage measures are low, their adoption by low-income households and farmers will present challenges. The same applies for some of the development measures, and strategies to overcome these implementation barriers are actively sought in this context.

2.3.7 Tailoring approaches to Asia's diversity

Strong economic growth in most of Asia, especially after 2000, has been associated with unprecedented increases in atmospheric pollution. While in South and Southeast Asia most of the precursor emissions of $PM_{2.5}$ continue along historic growth paths, policy interventions have led to a decoupling of emissions from economic growth in the High-income countries and recently in China (Figure 2.28).

A clean air strategy will vary in approach according to the context of each country and city, as well as its capacity to develop and implement measures. There is no uniform policy prescription for air quality that is applicable to all cities, countries and regions; such an approach would be neither possible nor desirable for a problem that is so diverse in local circumstances.



Note: Costs for the development measures themselves are not included.

FIGURE 2.26: AIR POLLUTION CONTROL COSTS FOR 2015 AND FOR THE DIFFERENT PORTFOLIOS OF MEASURES IN 2030

Source: GAINS 2017

Differing benefits

The impacts of the top 25 clean air measures on air quality and population exposure differ across Asia. Population exposure would be brought down to or below the WHO Guideline in Southeast Asia and the High-income countries, and below the WHO Interim Target level 1 in East and South Asia (Figure 2.29).

As shown in Figure 2.30, the full package of measures could eliminate exposure above the WHO Interim Target level 1 in Southeast Asia and the High-income countries, while in South Asia a small percentage of the population would remain exposed to $PM_{2.5}$ above the highest WHO Interim Target level 1.

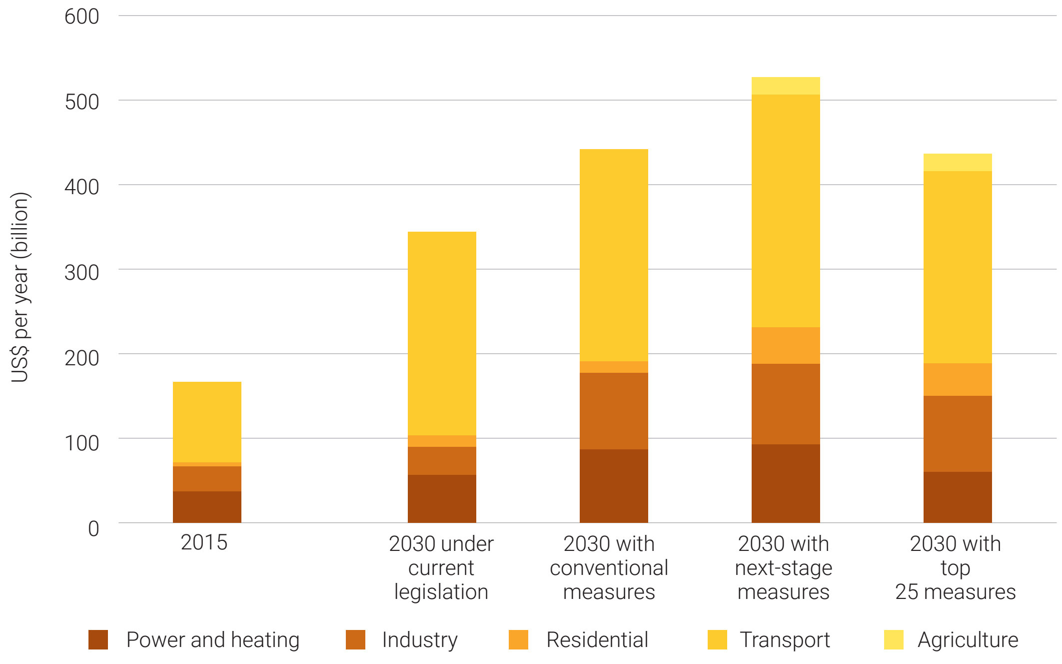
Differing priorities

Obviously, each of the 25 measures offers different potential air quality improvements, not only for all of Asia but even more so for specific countries, owing to the heterogeneities in social, economic, technological and geo-physical conditions across the region. Thus, any prioritization must take local aspects into account and will deliver different priority rankings.

Figures 2.31 to 2.34 list the impacts of the individual measures taken in each of the four sub-regions on mean population exposure within that sub-region. It should be noted that, due to the long-range transport of $PM_{2.5}$, exposure reductions also occur outside each sub-region; however, to highlight the immediate benefits from measures within the sub-region, these additional reductions are not included in the graphs.

East Asia

For East Asia, the priority measures that offer the largest further potential to improve ambient air quality differ markedly from the measures that are currently applied and have already avoided serious increases in pollution levels. While current legislation is rather effective in controlling the contributions from large industrial installations and



Note: Costs for the development measures themselves are not included.

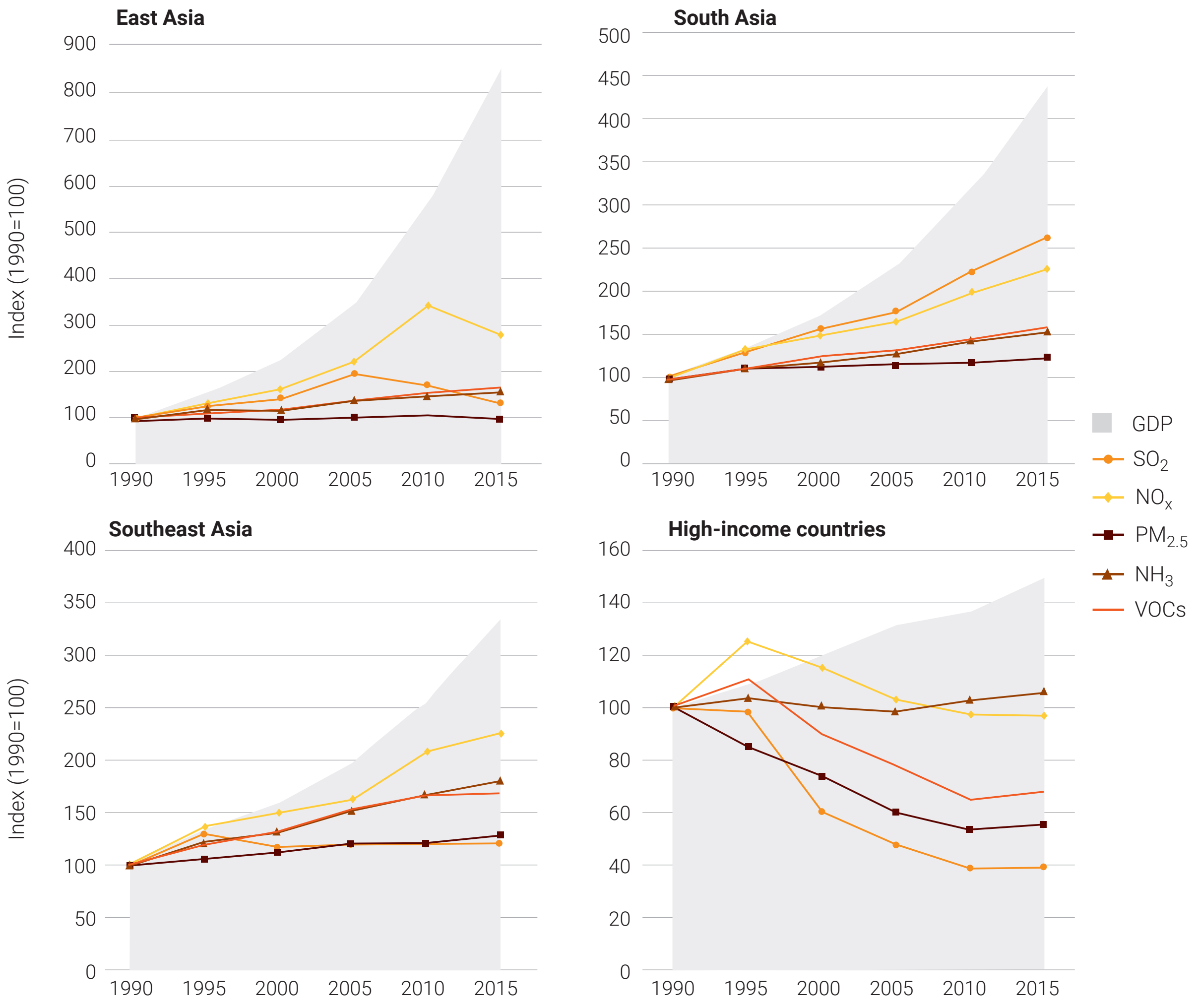
FIGURE 2.27: AIR POLLUTION CONTROL COSTS BY SECTOR, FOR 2015 AND FOR THE DIFFERENT PORTFOLIOS OF MEASURES IN 2030

Source: GAINS 2017

road vehicles (the darker segments in Figure 2.31), in the future the largest additional improvements emerge from clean cooking strategies to replace biomass and coal, the control of agricultural emissions from manure management and fertilizer use, energy efficiency policies, and restrictions on the open burning of agricultural and industrial waste (the lightest segments in Figure 2.31).

South Asia

For South Asia, measures that are already implemented (mainly controls for gasoline cars and some industrial processes) will have a comparable small impact on future air quality, while full and timely implementation of the recently decided new legislation should deliver large benefits on population exposure in the future. Beyond these measures, the analysis confirms the predominant importance of providing access to clean cooking. Further improvements are offered by a wide portfolio of measures, including full implementation of conventional emission controls for large industrial and power facilities, enhanced renewable energy, fertilizer use, the management of agricultural residues and residential waste, inspection and maintenance of vehicles and dust controls.



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

FIGURE 2.28: THE EVOLUTION OF GDP AND OF THE PRECURSORS OF $PM_{2.5}$ IN THE FOUR MODELLED SUB-REGIONS OF ASIA, 1990–2015

Source: IEA WEO 2016; GAINS model estimates

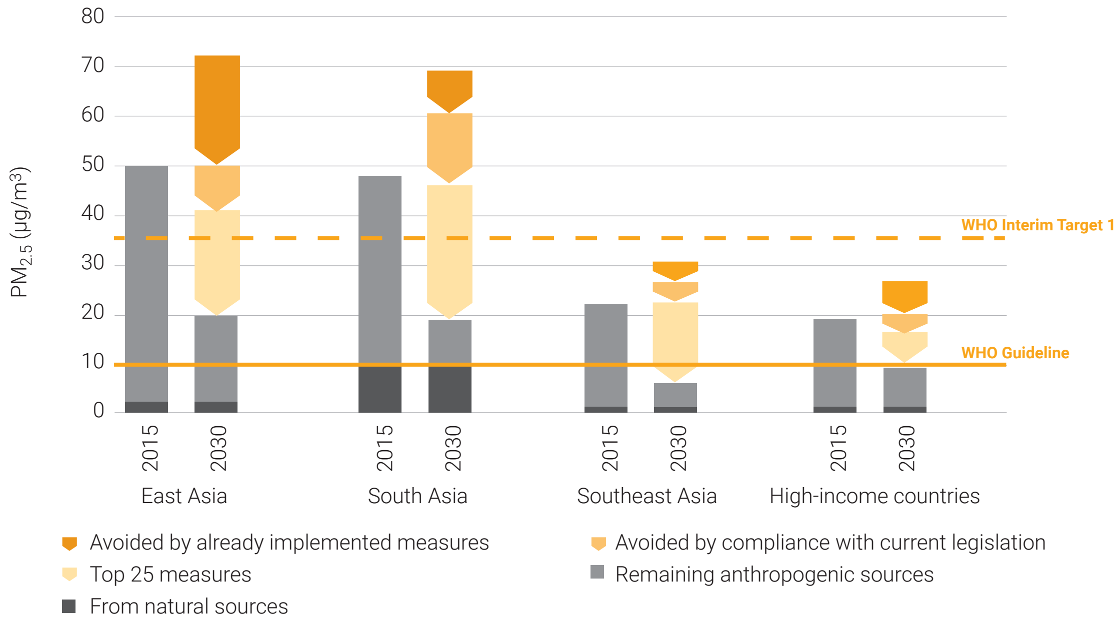


FIGURE 2.29: CHANGES IN POPULATION-WEIGHTED EXPOSURE TO PM$_{2.5}$ BETWEEN 2015 AND 2030, BY MODELLED SUB-REGION: THE BENEFITS OF IMPLEMENTING THE TOP 25 CLEAN AIR MEASURES AND REMAINING EXPOSURE

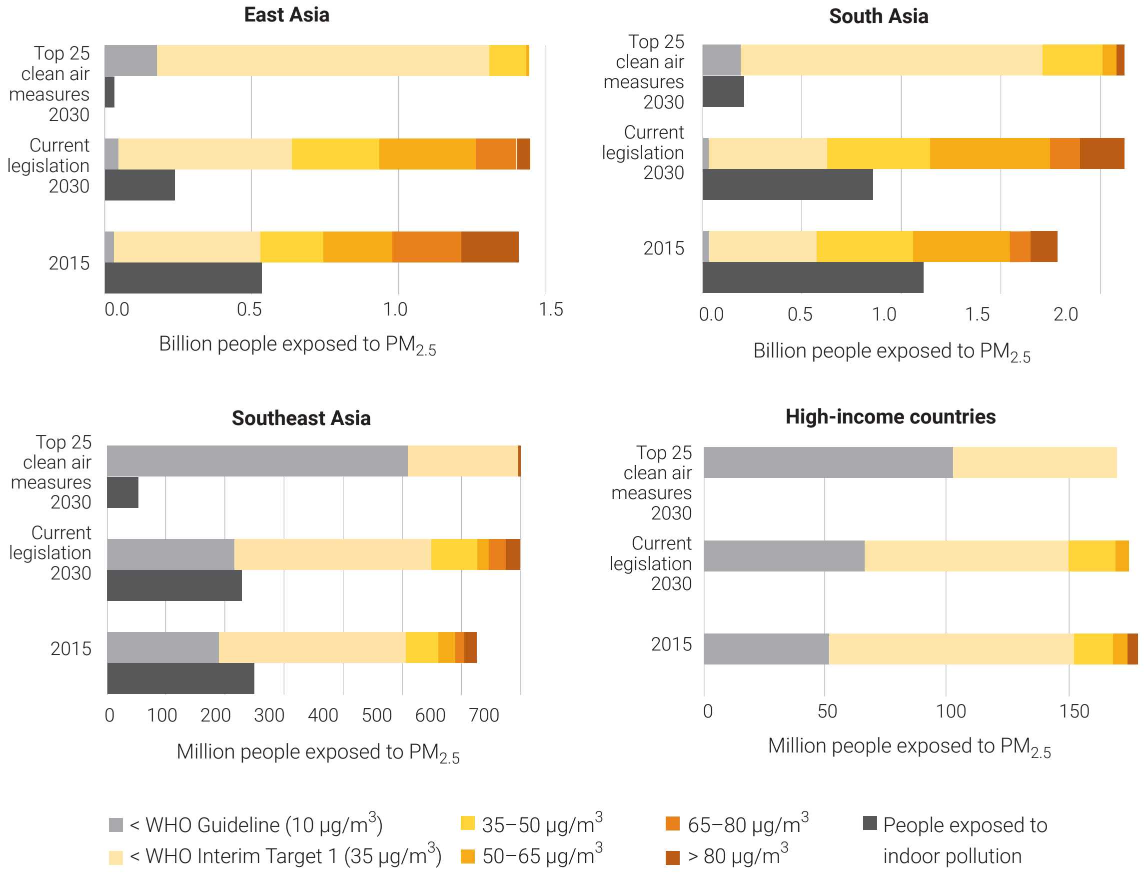


FIGURE 2.30: NUMBERS OF PEOPLE EXPOSED TO DIFFERENT LEVELS OF PM$_{2.5}$ IN AMBIENT AND INDOOR AIR, BY MODELLED SUB-REGION

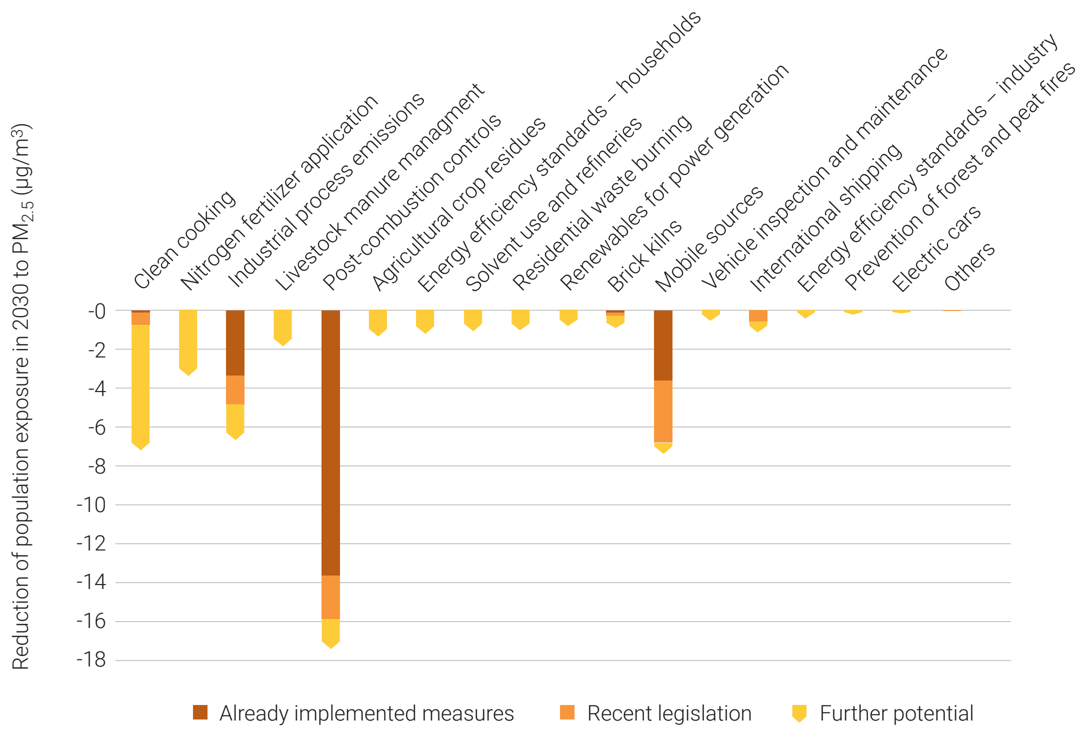


FIGURE 2.31: IMPACTS OF MEASURES TAKEN IN MODELLED EAST ASIA ON POPULATION EXPOSURE TO PM$_{2.5}$ WITHIN THE SUB-REGION, RANKED BY FURTHER POTENTIAL

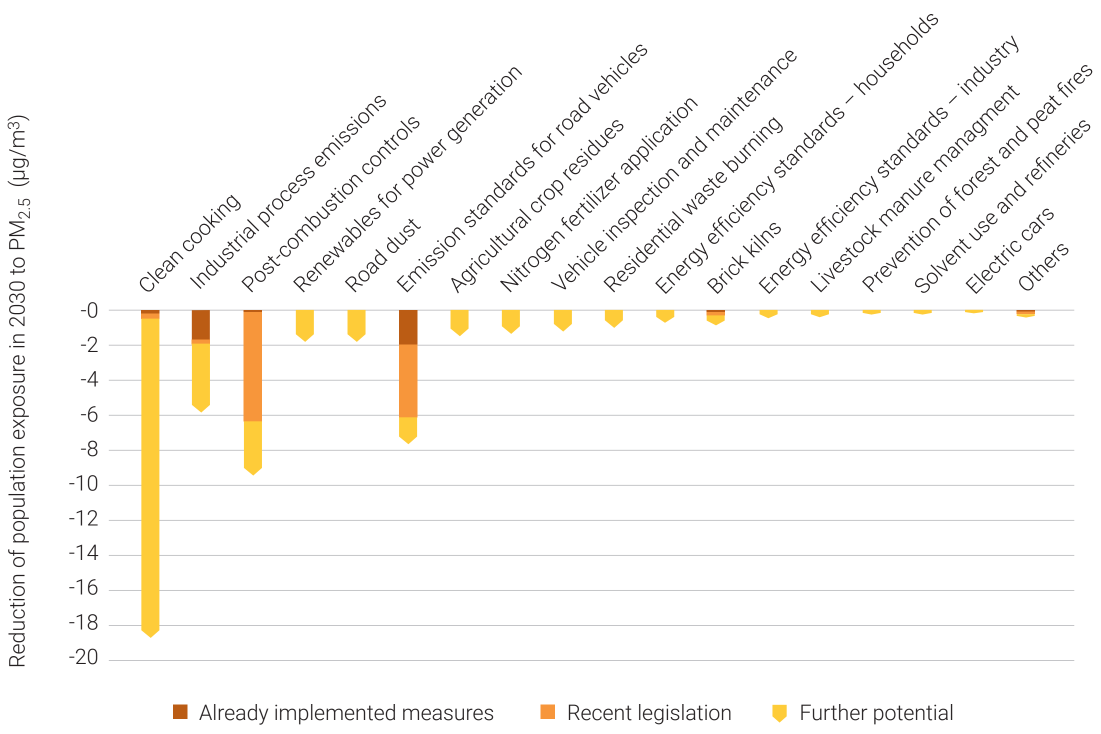


FIGURE 2.32: IMPACTS OF MEASURES TAKEN IN MODELLED SOUTH ASIA ON POPULATION EXPOSURE TO PM$_{2.5}$ WITHIN THE SUB-REGION, RANKED BY FURTHER POTENTIAL

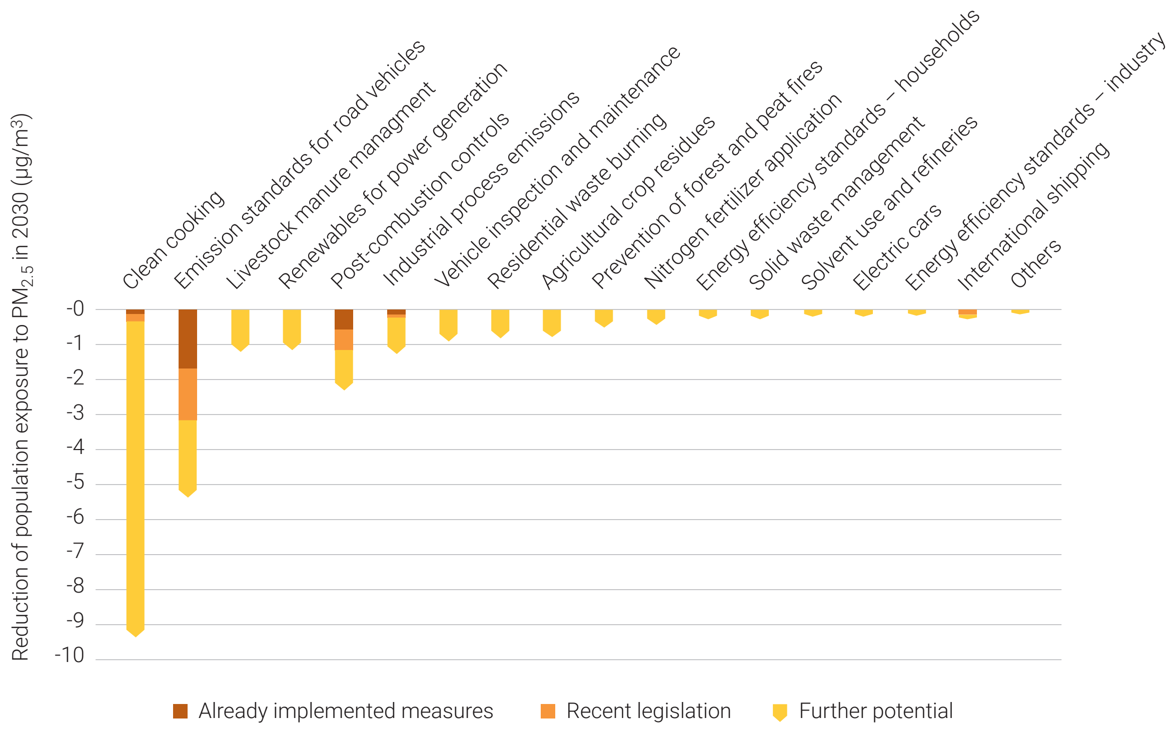


FIGURE 2.33: IMPACTS OF MEASURES TAKEN IN MODELLED SOUTHEAST ASIA ON POPULATION EXPOSURE TO $PM_{2.5}$ WITHIN THE SUB-REGION, RANKED BY FURTHER POTENTIAL

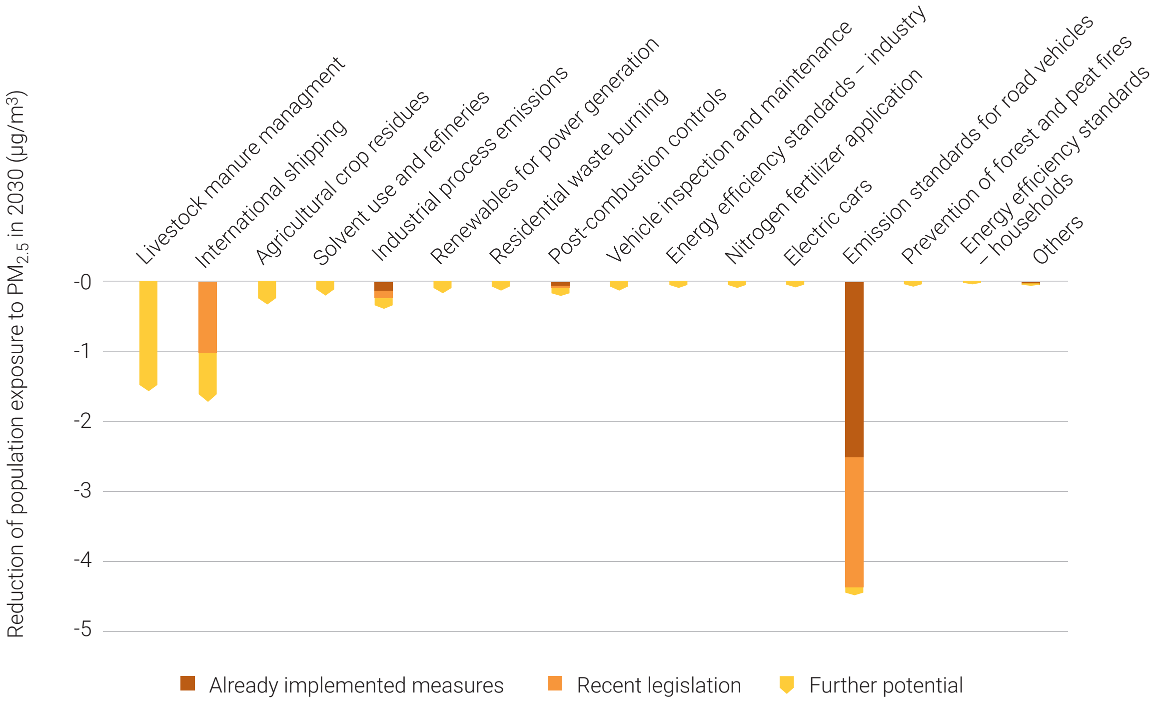


FIGURE 2.34: IMPACTS OF MEASURES TAKEN IN THE MODELLED HIGH-INCOME COUNTRIES ON POPULATION EXPOSURE TO $PM_{2.5}$ WITHIN THE SUB-REGION, RANKED BY FURTHER POTENTIAL

Southeast Asia

Compared to other sub-regions, current policies in Southeast Asia, with their focus on mobile sources, have delivered relatively small improvements in overall air quality. In the future, clean cooking offers by far the largest potential for further improvements, complemented by an extended application of the conventional pollution control measures for large industrial sources. However, measures in the agricultural sector affecting manure management, open burning of agricultural residues, forest fires and fertilizer use, as well as additional policies for the transport sector (inspection and maintenance, heavy- and light-duty diesel vehicles), will also be important (Figure 2.33).

High-income countries

As conventional emission controls are now widely applied in the high-income countries of Asia, further improvements in air quality require a re-orientation towards sources that received less attention in the past. In particular, control of NH_3 emissions, for example through improved manure management, will be important to restrict the formation of secondary particles. In addition, further controls from international maritime activities will deliver tangible benefits for air quality in these countries, as well as numerous measures that contribute to the SDG targets (Figure 2.34).

2.4. CONCLUSIONS

Successful decoupling of pollution from economic growth

In contrast to public perception, the policy actions taken in Asia in the last decade have led to a clear decoupling of SO_2 and NO_x emission trends from economic growth, confirming world-wide experience that pollution controls do not prevent further economic development. However, the actual benefits of these policy interventions on air quality are less visible, as they are often outweighed by the steep increase in economic activities.

Hypothetically, without the current policies, population-weighted exposure to harmful particulate matter would increase by about 50 per cent by 2030 given the envisaged economic growth of 80 per cent. Thus, the current policies deliver clear and significant returns on air quality and health benefits, even if they are not sufficient to significantly improve the present situation.

Current efforts insufficient to meet air quality standards

A full and timely implementation of the current policies will lead to further reductions in SO_2, NO_x, VOC and $PM_{2.5}$ emissions despite the envisaged further growth of the economy, although this will not deliver the massive improvements in ambient air quality that are required to meet national and international air quality standards. Among other factors, air quality benefits from these emission reductions will be outweighed by a steady growth in agricultural emissions, which will enhance the formation of secondary particles.

Beyond the current focus

To move towards national and international air quality standards, Asia will need to address those emission sources that are not the focus of current air quality management efforts in addition to safeguarding an effective, Asia-wide implementation of conventional emission control measures. In particular, controls of agricultural emissions that act as $PM_{2.5}$ precursors will be essential. Controlling solvent emissions will also be important to reduce population exposure to $PM_{2.5}$ as well as to ground-level O_3. Together, implementation of these measures could cut current population exposure to $PM_{2.5}$ in Asia by about 50 per cent.

New priorities

Controlling NH_3 emissions from manure management and fertilizer application, which act as important $PM_{2.5}$ precursors in ambient air, will be especially important. Proven measures are available to reduce these emissions at low cost, including the covered storage of manure, low-emission application of manure, reducing over-fertilization and optimized application of mineral fertilizers. Other priority measures relate to small combustion sources, the open burning of residential and agricultural waste, prevention of forest fires, effective inspection and maintenance schemes for vehicles, and the reduction of road dust.

Complementary benefits from development objectives

Actions that are prominently considered in the context of other development objectives, such as for climate change, clean water and sanitation, access to clean energy, sustainable cities, or responsible consumption and production, offer further means of improving air quality in Asia. Even if they are not primarily targeted on air pollution, they eliminate, or at least reduce, some of the most polluting activities. However, such development action alone, without targeted air quality measures, will not be sufficient to make progress towards air quality criteria; dedicated air quality management policies cannot be substituted by general development policies.

Measures tailored for Asia's diversity

A clean air strategy will vary in approach based on the context of each country and city, as well as its capacity to develop and implement measures. There is no uniform policy prescription for air quality that is applicable to all cities, countries and sub-regions; such an approach would be neither possible nor desirable for a problem that is so diverse in local circumstances.

In general, emission controls for agricultural sources (manure, fertilizer, burning of residues, forest fires) emerge as new priorities throughout Asia, while the urgency of providing access to clean cooking fuel is reconfirmed by this analysis.

In East Asia, where most conventional air pollution controls are already implemented at large scale, it will be critical that air quality management widens its current focus on large industrial sources and vehicles not only to agricultural sources, but also to enhanced energy efficiency and renewable energy policies.

In contrast, in South Asia effective implementation of recent pollution control legislation will be indispensable for stabilization of current pollution levels. Further improvements require acceleration of clean cooking programmes, wider application of conventional pollution controls, and policies that address other sources of pollution, including fertilizer application, management of agricultural residues and residential waste, enhanced renewable energy, effective inspection and maintenance of vehicles and reduction of road dust.

Priority areas are similar in Southeast Asia, with the prevention of forest fires as an additional focus.

As conventional emission controls are now widely applied in the High-income countries of Asia, further improvements in air quality require addressing agricultural sources such as manure management, maritime shipping and action that contributes to other development priorities.

A wide range of health and other development benefits

Despite uncertainties in the quantification of health benefits, the top 25 clean air measures could avoid several hundred thousand cases of premature death from ambient particulate matter pollution. In addition, by providing clean cooking fuel for 1.3 billion people, they would avoid annually more than a million premature deaths from indoor pollution, predominantly among women and children. Health impacts from exposure to ground-level O_3 could be reduced by 35 per cent, and crop yield losses by 45 per cent, equivalent to 20 million tonnes per year.

In addition, measures that improve air quality and reduce exposure to air pollution directly contribute to multiple SDGs.

Contributions to the climate agenda

Due to the co-control of air pollutants, SLCPs and long-lived greenhouse gases (CO_2), the top 25 clean air measures could provide a net reduction in the rate of global temperature increase by about one third of a degree Celsius in 2050, and thereby significantly contribute to the Paris Agreement target of a more sustainable lower rate of warming.

CHAPTER 3

Closing the implementation gap: bringing clean air to the region

3.1 INTRODUCTION

Millions of people in the Asia and Pacific region could enjoy longer, healthier lives if measures to control and prevent air pollution were successfully implemented

Chapter 2 drew on the Greenhouse gas–Air pollution Interactions and Synergies (GAINS) model and a suite of others to identify measures that could significantly reduce air pollution in Asia and the Pacific. The modelling shows that effective implementation of 25 measures could prevent exposure to dangerous levels of air pollution, while avoiding premature deaths, increasing food security, and mitigating near- and long-term climate change in the region. In achieving these benefits, the 25 measures could help the region make significant progress towards meeting several Sustainable Development Goals (SDGs), particularly SDGs 3, 11 and 13 (Elder and Zusman 2016).

Chapter 3 reviews broad trends and concrete examples of implementation for the three sets of options making up the top 25 measures: conventional controls, next-stage measures and development priority measures. These three groups of measures offer alternatives from which countries can select nationally appropriate options. Though the choice and timing of those options will vary across the region, countries are likely to go through a relatively similar process of building on increasingly robust science to inform their selection. That process frequently begins with environmental agencies acquiring initial air quality monitoring data to identify and recognize air pollution problems. This initial phase sets the stage for improved monitoring data and emissions inventories that can contribute to policies aimed at reducing emissions. Following the development of inventories, analyses of the apportionment of emission sources will tend to form the basis for policies meant to enhance overall air quality. A final stage will frequently consist of developing health-impact, cost-effectiveness and/or cost-benefit analyses to determine which interventions maximize the health and other benefits of clean air (Figure 3.1). Though this report presents regional results, national-level data are available on request from the UN Environment Asia and Pacific Regional Office to help decision makers consider moving through this process.

This chapter is divided into four sections. In section 3.2, it provides an overview of conventional controls, demonstrating that national environmental agencies have often worked with other agencies and industries to introduce air quality standards and legislation to implement these kinds of controls. It then examines relevant next-stage and development

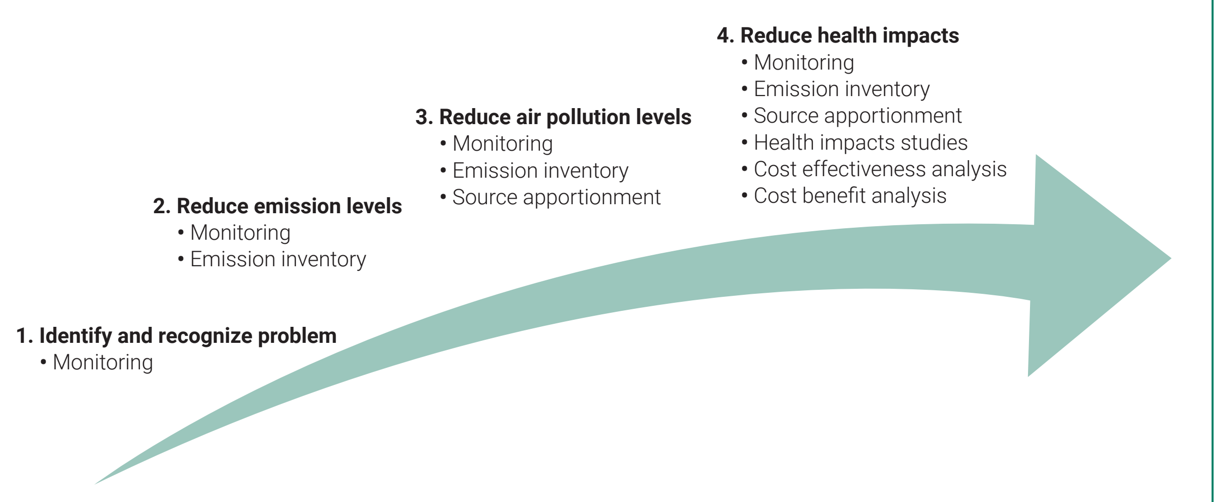


FIGURE 3.1: STRENGTHENING THE SCIENTIFIC BASIS FOR AIR QUALITY MANAGEMENT OVER FOUR STAGES

priority measures in sections 3.3 and 3.4, highlighting the diverse range of actors and institutions involved in implementing these options. Section 3.5 summarizes some of the factors behind successful implementation of the measures and reflects the importance of multi-stakeholder governance and innovative finance to improve compliance with the measures in the region.

TABLE 3.1: THE TOP 25 CLEAN AIR MEASURES

Regional application of conventional measures	
Post-combustion controls	Introduce state-of-the-art end-of-pipe measures to reduce sulphur dioxide, nitrogen oxides and particulate emissions at power stations and in large-scale industry
Industrial process emissions standards	Introduce advanced emissions standards in industries, e.g., iron and steel plants, cement factories, glass production, chemical industry, etc.
Emissions standards for road vehicles	Strengthen all emissions standards; special focus on regulation of light- and heavy-duty diesel vehicles
Vehicle inspection and maintenance	Enforce mandatory checks and repairs for vehicles
Dust control	Suppress construction and road dust; increase green areas
Next-stage air-quality measures that are not yet major components of clean-air policies in many parts of Asia and the Pacific	
Agricultural crop residues	Manage agricultural residues, including strict enforcement of bans on open burning
Residential waste burning	Strictly enforce bans on open burning of household waste
Prevention of forest and peatland fires	Prevent forest and peatland fires through improved forest, land and water management and fire prevention strategies
Livestock manure management	Introduce covered storage and efficient application of manures; encourage anaerobic digestion
Nitrogen fertilizer application	Establish efficient application; for urea also use urease inhibitors and/or substitute with, for example, ammonium nitrate
Brick kilns	Improve efficiency and introduce emissions standards
International shipping	Require low-sulphur fuels and control of particulate emissions
Solvent use and refineries	Introduce low-solvent paints for industrial and do-it-yourself applications; leak detection; incineration and recovery

TABLE 3.1: THE TOP 25 CLEAN AIR MEASURES (contd.)

Measures contributing to development priority goals with benefits for air quality	
Clean cooking and heating	Use clean fuels – electricity, natural gas, liquefied petroleum gas (LPG) in cities, and LPG and advanced biomass cooking and heating stoves in rural areas; substitution of coal by briquettes
Renewables for power generation	Use incentives to foster extended use of wind, solar and hydro power for electricity generation and phase out the least efficient plants
Energy efficiency for households	Use incentives to improve the energy efficiency of household appliances, buildings, lighting, heating and cooling; encourage rooftop solar installations
Energy efficiency standards for industry	Introduce ambitious energy efficiency standards for industry
Electric vehicles	Promote the use of electric vehicles
Improved public transport	Encourage a shift from private passenger vehicles to public transport
Solid waste management	Encourage centralized waste collection with source separation and treatment, including gas utilization
Rice paddies	Encourage intermittent aeration of continuously flooded paddies
Wastewater treatment	Introduce well-managed two-stage treatment with biogas recovery
Coal mining	Encourage pre-mining recovery of coal mine gas
Oil and gas production	Encourage recovery of associated petroleum gas; stop routine flaring; improve leakage control
Hydrofluorocarbon (HFC) refrigerant replacement	Ensure full compliance with the Kigali Amendment

3.2 CONVENTIONAL EMISSION CONTROLS

Measures that are widely adopted in the current emission control legislation of Asian countries will avoid a further deterioration in air quality

One of the key findings in Chapter 2 is that, even with economic growth of about 80 per cent by 2030, the effective implementation of conventional emission controls could maintain mean population exposure to air pollution at the current levels and reduce exposure in some areas. For many countries in Asia and the Pacific, ambient air quality and emissions standards are the starting point of efforts to encourage power plants, industries and other sources to adopt these conventional controls. When formulating standards, environmental agencies across a growing number of countries in Asia and the Pacific have become better at making the case for *introducing* and then *tightening* standards. This is evident in both the increasing overall number of countries adopting some level of standards and in the number of countries with the more stringent levels of standards (Figures 3.2 and 3.3). However, there is also scope for countries to bring standards in line with the criteria of the World Health Organization (WHO).

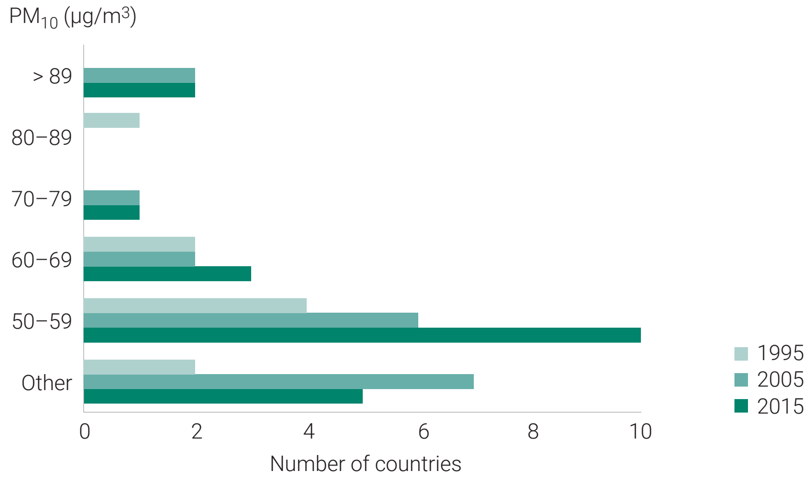


FIGURE 3.2: NUMBER OF COUNTRIES WITH DIFFERENT LEVELS OF AMBIENT AIR QUALITY STANDARDS FOR PM_{10}

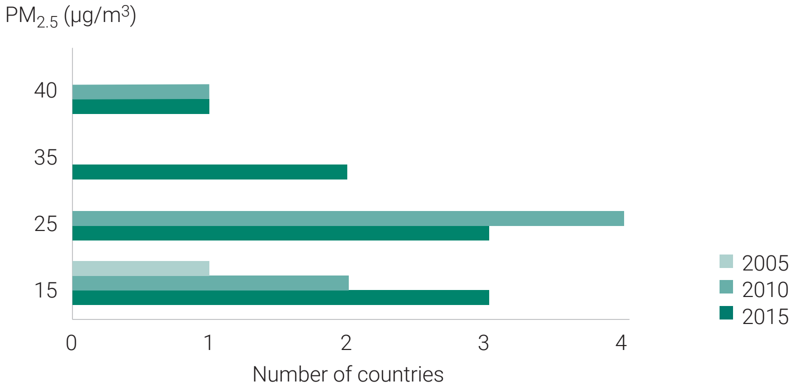


FIGURE 3.3: NUMBER OF COUNTRIES WITH DIFFERENT LEVELS OF AMBIENT AIR QUALITY STANDARDS FOR $PM_{2.5}$

Source: Clean Air Asia 2016

For energy and industrial sources, governments have progressively tightened production and performance standards and encouraged technical or process changes to reduce emissions (UNESCAP 2001). In countries ranging from the Republic of Korea to Thailand, these regulatory changes have encouraged power plants to install flue gas desulphurization and other emission control technologies (Simacha 2015; Wang *et al*. 2014). In some cases, the stiffening of regulations has had an even greater effect. For instance, India has recently moved towards energy-efficient supercritical technologies due in part to the ongoing implementation of increasingly stringent standards for old and new coal-fired power plants (MoEFCC 2015). In other instances, as occurred in India's capital of Delhi, phasing in stringent standards has resulted in the shutdown of power plants or a shift to gas as the fuel of choice (Singh and Prasad 2015). While tighter standards can encourage investment in pollution control technologies or broader structural change, there is often a need for legally backed financial incentives that bring about these shifts. In countries ranging from China to Mongolia, legislation that provides for air pollution fees has created those incentives (Clean Air Asia 2016a; Dasgupta *et al*. 2001).

The impacts of regulation can also be felt in certain energy-intensive heavy industries. In fact, in some cases, regulations like those mentioned above have helped stimulate investments in cleaner technologies that have spread across the region. Waste heat recovery (WHR) in China's cement sector is a case in point (Box 3.1). While significant investments in pollution control and prevention technologies could substantially improve air quality (IEA 2016a), realizing the scalable gains illustrated by China's cement sector often requires compliance incentives and clear evidence of cost savings that can encourage multiple industries to invest in pollution control technologies (Liu 2015).

Many countries in the Asia and Pacific region could adopt conventional controls at early stages of their development

Clean air action plans are additional vehicles that governments employ to control air pollution. In some instances, these plans start with national governments responding to emerging policy priorities. In 2012, China's national government released new ambient air quality standards and technical regulations for an air quality index as part of a wide-ranging effort to curb fine particulate matter ($PM_{2.5}$). That effort laid the foundation for an Air Pollution Prevention and Control Plan in 2013 that set sub-regional targets for $PM_{2.5}$ reductions in Beijing-Tianjin-Hebei (25 per cent by 2017 compared to 2012), Yangtze River Delta (20 per cent), and Pearl River Delta (15 per cent). More recently, India's government adopted the National Clean Air Programme (NCAP) that is, *inter alia*, expanding the air monitoring network; improving the dissemination of data and public outreach; and calling for plans for prevention, control and abatement of air pollution (MoEFCC 2018). In other instances, sub-national governments have been

BOX 3.1: WASTE HEAT RECOVERY IN NINGGUO, CHINA

In August 1995, China's then National Planning Commission and Japan's New Energy and Industrial Technology Development Organization (NEDO) signed an agreement for a WHR power generation demonstration project. That agreement led to work with Kawasaki Heavy Industry to install WHR at the Ningguo cement plant of Conch Cement in 1998. Conch Cement took the lead in the diffusion of large-scale WHR after the success of the pilot project. Kawasaki Heavy Industry and Conch Cement established three joint ventures over the period 2006–2009, and by the end of December 2016, a total of 279 clinker production lines based in 23 Chinese provinces and municipalities had been equipped with 207 Conch-Kawasaki WHR systems. An additional 23 systems were set up in 37 clinker production lines in a further nine developing countries in Asia (Liu 2015).

behind important regulatory changes. Kawasaki, Japan, introduced its own 'total emission control system' (also known as the Kawasaki Method), which began with a city ordinance followed by the implementation of more stringent environmental quality standards and corresponding action (Clean Air Asia 2016b). Clean air action plans do not always start at the national level. Cities such as Can Tho, Viet Nam, have also developed action plans to target locally relevant sources (Bang *et al*. 2017).

The regulation of the transport sector, particularly diesel engines, offers another conventional control with potential benefits in the region. These gains originate from more stringent vehicle emissions standards. In many parts of the region, environmental agencies have become more adept at working with transport agencies, vehicle manufacturers and the fossil fuel industry to make these standards tighter. Cooperation with oil refineries is particularly important since attaining stronger standards requires lowering the sulphur concentration in diesel fuel to 50 parts per million (ppm) and where possible to 10 ppm. This is because some diesel control technologies cannot function properly above these levels. In the Philippines, the gradual tightening of regulations motivated the Petron Corporation to begin supplying 10 ppm gasoline in 2016 (Voltaire Palaña 2016). Petron also recently announced the roll-out of diesel fuels with a maximum sulphur content of 10 ppm in Malaysia (Petrol World 2016) – a significant change as Malaysia currently supplies 500 ppm sulphur diesel and gasoline.

Fuel switching, another solution to mobile source pollution, has also been practised in some parts of Asia. Sometimes the impetus for regulatory change comes from institutions outside government agencies. India's Supreme Court, for example, issued a decision that required the entire Delhi public transport fleet – buses, taxis and auto-rickshaws – to switch to compressed natural gas (CNG) (Mehta 2001). There are currently 1,094 CNG stations in India due to this landmark decision (PNGRB 2018). New technologies and actors have also become important advocates for innovative reforms. The International Council for Clean Transport (ICCT), an international non-profit organization that provides research on environmental regulators, is working with 20 megacities to introduce battery electric buses as a low-cost soot-free option (Miller *et al*. 2017).

Non-technical solutions can help reduce emissions from heavy-duty commercial vehicles. For example, effective logistics and route planning for freight vehicles can avoid unnecessary travel and cut emissions (UNCRD 2013). There can also be effective combinations of measures – for instance, replacing older buses can open an opportunity for route rationalization and optimization that offers complementary improvements in service quality.

BOX 3.2: TAXATION POLICIES AND HYBRID VEHICLES IN ULAANBAATAR

In total, 411,400 of the 675,000 vehicles in Mongolia are registered in Ulaanbaatar (Department of Traffic Police Ulaanbataar 2016). Many of these vehicles are older, second-hand cars imported from Japan and Korea. A study from the Ulaanbaatar Transportation Department, for instance, found that 91 per cent of all vehicles on the road are from Japan and Korea. To reduce mobile source emissions, Mongolia introduced an excise tax exemption and a reduction in taxes on the import of hybrid, electric and LPG-fuelled vehicles in 2006. The existing excise tax amounts were based on the vehicle's year of production and engine size, with costs ranging from US$ 500 to US$ 5,000 per vehicle. In addition, all imported vehicles were required to pay import duty and value-added tax. The removal of the taxes led to a significant increase in low-emission vehicles in Ulaanbaatar. Official figures indicate there were 74,437 hybrid and 11,981 LPG-fuelled cars in Ulaanbaatar by end of 2016 (Statistical Agency of Ulaanbataar 2016).

For many developing countries in Asia and the Pacific, much of the air pollution comes from older second-hand cars imported from developed countries. To help reduce emissions from these imported vehicles, Mongolia introduced an excise tax policy favouring hybrid and electric vehicles that has changed the second-hand car-purchasing practices of low- and middle-income families. As a result, the number of hybrid cars in the capital Ulaanbaatar reached 74,437 at the end of 2016, so that now 22 per cent of the city's vehicles – including buses, trucks and special-purpose vehicles – are hybrids (Statistical Agency of Ulaanbataar 2016) (Box 3.2).

Apart from technical solutions, inspection and maintenance (I&M) programmes that remove the highest emitters are a critical component of a well-designed diesel control strategy. In Tokyo, Japan, a well-publicized and staffed effort to inspect vehicles helped remove the city's highest emitters. For the 13,000 buses in Jakarta, an I&M programme reduced diesel soot by 30 per cent and fuel consumption by 5 per cent (UNEP 2009). A review of several programmes in Asia found that the following design features were important for successful I&M:

- centralized I&M systems developed through multi-agency collaboration at the early stages of planning, with a self-funding mechanism for regular audits of test centres;
- comprehensive and recurrent fleet characterization to guide I&M policies and strategies;
- timely and appropriate strengthening of I&M policies and emissions standards based on the characteristics of the fleet and considering existing vehicle technologies, while advancing towards cleaner emissions;
- a strong vehicle maintenance and repair service industry that is able to deal with vehicles that fail emissions testing;
- consistent enforcement and reliable detection technologies that build and maintain public trust, awareness and participation;
- complementary policies on vehicles that enter and exit the active fleets (Clean Air Asia 2016c).

Most conventional air quality controls are reinforced by relevant legislation. For some countries in Asia and the Pacific, legislation has become more coherent as awareness of the adverse impacts of air pollution has increased. In India, for example, several sector-specific laws include provisions related to air pollution. India's Air Pollution Prevention and Control Act of 1981 depends on the performance of its Motor Vehicles Bill of 1988 (amended in 2007), the Auto Fuel Policy of 2002, the National Environment Policy of 2006, and the National Green Tribunal Bill of 2009 (from the National Environmental Tribunal Act of 1995) (Clean Air Asia 2010).

Another set of conventional controls aims to reduce fugitive dust from unpaved roads and infrastructure development. This dust is a serious air pollution problem in areas with expanding transport and construction networks – for instance, some cities in India attribute more than half of their $PM_{2.5}$ to this dust. It can also be a major issue in areas with quickly expanding transport networks and proximity to high winds. In Mongolia, a phenomenon known

BOX 3.3: TOKYO METROPOLITAN GOVERNMENT DIESEL STRATEGY

An interesting example of a diesel control strategy can be found in Tokyo, Japan. In 1999, the Tokyo Metropolitan Government established Operation No Diesel in response to growing public concern over air pollution. This was followed a year later by the promulgation of a new Ordinance on Environmental Preservation that had as its centrepiece the Countermeasure Against Vehicle Pollution programme. The countermeasure programme included diesel emission control regulations requiring in-use diesel vehicles to be retrofitted with emission control systems or face a non-compliance travel ban in Tokyo. This was accompanied by a set of other measures that were designed to limit idling, prohibit heavy-oil fuels, and deploy vehicle pollution inspectors to remove high-emitting vehicles (Rutherford and Ortolano 2008).

as silt-loading illustrates this problem: an increase in heavier vehicles that travel over greater distances places stresses on unsealed road surfaces, creating considerable emissions of particulates (Guttikunda *et al*. 2013).

Several technical options are available to policy makers to address these problems. Next to sealing unpaved surfaces, water suppression that helps gather dust to larger entities that are unlikely to be re-suspended may be the most feasible near-term option (Watson *et al*. 2000). Research in developed countries has generated a range of chemical-based road dust suppressants (Gillies *et al*. 1999). On existing paved surfaces, pressurized sprays and street cleaning with mechanical equipment can vacuum or wash dust into drainage systems (Watson *et al*. 2000). In some cases such as the city of Rajhashi, Bangladesh, forward-looking politicians and citizens have engaged in a concerted effort to plant more trees and shrubs to suppress the dust (Graham-Harrison 2016).

3.3 NEXT-STAGE MEASURES

The implementation of conventional pollution control and prevention programmes will help to prevent further deterioration in air quality despite the 80 per cent economic growth anticipated in Asia by 2030 (Chapter 2). Further measures, however, will be required to reduce the health impacts of ambient air pollution that are already apparent. In addition, conventional measures will not address the impacts of indoor exposure to air pollution.

This section focuses on a more diverse collection of measures that goes beyond conventional emission controls. Interventions range from managing agricultural residues sustainably to industrial controls on solvents. Diversity is also evident in the types of stakeholders involved in crafting and implementing next-stage controls.

3.3.1 Agricultural residues

Open burning involves the combustion of various biomass materials such as crop residues (Marshall et al. 1996). It is a particularly large source of air pollution in Southeast Asia, accounting for 5–30 per cent of total anthropogenic emissions (Streets *et al*. 2003). Crop residue burning has strong seasonality. It significantly increases $PM_{2.5}$ concentrations in the dry season and occasionally contributes to local and regional pollution episodes (Kim Oanh 2013). In Southeast Asia, burning is often carried out to clear land of crop residues in order to facilitate or accelerate crop rotation (Kim Oanh 2013). It may also be used to keep underbrush from encroaching on orchards or to clear land for cultivation. A majority of wildfires, ranging from 50–95 per cent of all wildfires according to national estimates, also originate from open burning in the agricultural sector. Burning in some countries, such as Nepal, has increased in recent years due to societal change – as agricultural workers leave for salaried positions overseas, less rural labour is available to gather straw for animal bedding.

Measures to address the problem include bans on open burning, though the effectiveness of instituting bans without engaging affected communities is questionable and often counter-productive. Despite the bans the burning continues, often with passive – but occasionally violent – farmer protests (Mohan 2017). A potentially more effective set of measures involves working with farmers to provide alternatives to burning, such as low- or no-till conservation agriculture. These methods, which involve planting seeds directly through stubble, also bring adaptation benefits such as increased resilience to extreme weather – both drought and heavy rains – and a decreased need for fertilizer. The benefits accruing from climate resilience and low fertilizer inputs lead to lower costs. In such cases, livestock manure and cover crops can also be used for soil enrichment. Another no-burn alternative involves the on-farm or commercial use of crop residues (Kim Oanh 2013) (Box 3.4). On-site microbial degradation may be an effective way forward to avoid the burning of crop residues. The widespread use of mechanical rice-straw baling machines can convert above-ground biomass into compressed straw bales, help farmers prepare land for the next crop cycle, and derive additional income from selling the bales (Kanokkanjana and Bridhikitti 2007). In India, the government has taken a cross-sectoral approach, asking power companies to buy agricultural waste from farmers and convert it into biomass pellets that can be co-fired with coal (PIB 2018).

In addition, India is exploring the potential for biomass gasification, the use of seed drills that incorporate residues as a mulch (Happy Seeders), and bio-methanation processes that put agricultural residues to productive use and make open burning bans more effective. Off-site uses for crop residues, such as the production of biogas for household fuel or electricity generation, growing mushrooms, brick production or use as silage or animal bedding, can also offer win-win solutions.

3.3.2 Prevention of peat and forest fires

Forest fires are a long-running problem in Asia. Many of the most serious fires are in Southeast Asia, spread primarily by deliberate burning of agricultural residues and by aggressive land clearance that has increased with the expansion of plantations for rubber, palm oil and paper production (Jerger 2014). Economics are the main driver behind the burning: clearing land mechanically can cost between 1.5 and at most 40 times as much as clearing land with fire and chemicals (Salim 2007) if the residue is not put to commercial use.

Promoting no-burn methods in the agricultural sector as a whole may decrease forest fires by up to 90 per cent in some countries. In other cases, where land clearance causes the majority of fires, the creation of a market for useful products may provide greater incentives to use no-burn methods. These can be introduced independently or with support for the purchase or lease of clearing equipment, or through the outright monetizing of conserved forest regions as carbon sinks.

Much of the effort to solve these problems has focused on transnational and regional arrangements, particularly the Association of Southeast Asian Nations (ASEAN) Agreement on Transboundary Haze Pollution (AATHP). Views on the agreement differ. To some extent, it has helped give rise to collaborations such as the Adopt-A-District programmes that saw Malaysia and Singapore provide awareness-raising and community-building support for the parts of Indonesia where the fires originated. While these efforts helped promote zero-burning practices and provide communities with alternative livelihoods, such as pineapple farming, they had a limited effect on those industries that contributed most to the burning (Quah and Varkkey 2007). More recently, Indonesia's decision to ratify the Haze Agreement has given rise to a Haze-free Roadmap and greater enthusiasm over means of implementation that would help support the provisions in the roadmap (ASEAN 2017) (Box 3.5).

3.3.3 Manure management

Animal manure is a key source of ammonia, which acts as an important component in the formation of secondary particles in the atmosphere. The

BOX 3.4: LIMITING OPEN BURNING IN THAILAND

In Thailand, open burning of crop residues is practised to prepare land for faster crop rotation. Although the government has implemented bans on open burning and 'stop forest fires' campaigns for several years, farmers continue burning because it offers an easy, inexpensive and quick way to prepare for a new round of crops. Since most bans have been implemented without integrating farmer education on the negative soil and crop-yield impacts of burning – such as increased erosion and greater need for fertilizers – or support for viable no-burn alternatives, little progress has been made. Thailand has therefore sought other approaches to help local governments halt open burning. These include directly involving landowners, farmers and businesses in emission controls through public relations activities, training, workshops and field visits. The government has also promoted off-site use of agricultural residues through a business model that creates a sustainable market for crop residues. Finally, the government has promoted technologies that plough rice straw and corncobs into fields for on-site degradation.

BOX 3.5: ROADMAP ON ASEAN COOPERATION TOWARDS TRANSBOUNDARY HAZE POLLUTION CONTROL WITH MEANS OF IMPLEMENTATION (2016–2020)

Indonesia's ratification of the ASEAN AATHP in September 2014 has helped to advance the agreement's work programme. On 11 August 2016, the Roadmap on ASEAN Cooperation towards Transboundary Haze Pollution Control with Means of Implementation (2016–2020) – the Haze-free Roadmap – was adopted by the 12th Meeting of the Conference of the Parties to the AATHP.

The Haze-free Roadmap serves as a strategic, action-oriented and time-bound framework for the implementation of collaborative action to control transboundary haze pollution in the ASEAN region, aiming to achieve the vision of a Transboundary Haze-free ASEAN by 2020.

In recent years, the Haze Agreement has made significant progress as measured by the following Haze-free Roadmap indicators:

- an increase in the number of days with good or moderate air quality in terms of the Pollutant Standard Index (PSI) or Air Quality Index (AQI), based on PM_{10} and/or $PM_{2.5}$ concentrations;
- a reduction in the number of hotspots below Alert Level 2 under the ASEAN Standard Operating Procedure on haze;
- a decrease in the transboundary haze pollution area.

Source: ASEAN 2017

proportion of total nitrogen (N) intake that is excreted and partitioned between urine and faeces depends on the type of animal, intake of dry matter and N concentration of the diet. About 80–95 per cent of ingested N is excreted in dung and urine. As the N content of the diet increases, so does the amount in the urine. Where the ingestion of N compounds is high, more than half of these compounds are excreted as urine (IPCC 1997).

Animal manure is not often managed in a systematic manner in Asia and the Pacific. Most individual farm units have small open pits where manure is dumped and composted for later field application, while many of the large industrial farms are decoupled from crop production areas and therefore deal with manure as waste rather than a resource in the form of organic fertilizer. Among premium producers, however, the emphasis on organic cultivation is prompting farmers to manage animal manure scientifically and thereby better meet the fertilizer requirements of their crops. Improving manure management practices, including the use of closed storage tanks and rapid incorporation of manure into soil following application, are effective means of reducing ammonia losses.

3.3.4 More efficient fertilizer application

The use of chemical N-based fertilizers and agricultural productivity have both risen sharply in Asia in the last four decades. At present, total fertilizer nutrient consumption in Asia accounts for 60 per cent of global use, with China and India the largest producers and consumers of N-based fertilizers (FAO 2014). Unfortunately, the use efficiency of N-based fertilizers can be as low as 30–35 per cent, resulting in significant losses of N compounds to the atmosphere and ecosystems. Asia's policy makers have become aware of these losses and of the heavy subsidy burden, which has been estimated at around US$ 7 billion for India alone (Sutton *et al*. 2017).

National governments have adopted measures to reduce the loss of N-based fertilizers while curbing environmental impacts and the financial losses of subsidies. The government of India, for example, introduced an initiative in 2015 that requires coating the entire urea-N production with neem oil, a nitrification inhibitor that can reduce the loss of urea by about 10–15 per cent. Industry and research institutes in India have also introduced the 4Rs Nutrient Stewardship Programme – right form, rate, method and time of application – to manage fertilizer N, to increase its efficiency of use, matching fertiliser supply with crop demand; minimizing N application in the wet season to reduce leaching, and supplying fertilizers to the plant rather than the soil. Other promising techniques – such as the split application of N, slow- and controlled-release fertilizers, neem-coated urea, speciality fertilizers and fertigation, and leaf colour charts – could reduce India's use of N-based fertilizer use by 20–25 per cent by 2030.

These kinds of solutions have not been limited to India. Bangladesh has introduced innovative ways of increasing the use efficiency of N-based fertilizers with urea super granules, deep placement of urea, bio-organic fertilizers and low-input crop varieties. These measures have increased rice yield by 15–20 per cent and reduced the use of N-based fertilizers by 20–30 per cent (Islam *et al*. 2016). Although the adoption of urea super granules on a large scale has encountered some application problems, Bangladesh continues to promote this technology. Sri Lanka is also adopting the 4Rs Stewardship Programme to address low use efficiency and its effects on groundwater contamination and air pollution. Similarly, Pakistan is considering using new fertilizer formulations, including inhibitors.

Small and medium-sized enterprises and infrastructure development may require innovative management approaches to reduce emissions

3.3.5 Brick kilns

Brick kilns are a major source of air pollution in many developing countries in Asia and the Pacific. For countries suffering from their emissions, one way to reduce the pollution involves shifting from relatively energy-intensive fixed chimney kilns to more efficient zig-zag, vertical shaft brick and tunnel kilns. The overall impact of these shifts depends on the type of fuel and technology, and the efficient operation and maintenance of the new technologies. Perhaps the greatest variable in determining the effectiveness of new technology is the degree to which longstanding production practices can be changed. Countries have sought to change those practices through the phasing out of fixed chimney technologies (Bangladesh) or sustainable building policy that aims to improve efficiencies in brick production (Viet Nam). In some instances, researchers and practitioners have taken advantage of otherwise destructive windows of opportunity to effect meaningful change. Following a major earthquake in Nepal in 2015, for instance, a consortium of policy makers, researchers and international development specialists worked with kiln owners to introduce more efficient technologies that have begun to take hold in the areas around Kathmandu, with growing interest in other countries in Asia (Box 3.6) (Pradhan *et al*. 2018).

3.3.6 Shipping emissions

Control of shipping emissions is important to air quality management and public health for coastal port cities and regions with significant marine traffic. Owing to concerns about port competitiveness and trade opposition, port cities in Asia and the Pacific have been slow to introduce regulations on marine fuels. Indeed, a lack of information about shipping emissions as a pollution source has also hampered a better appreciation of its implications for air pollution policy, evaluation of the public health burden, and strategies to address climate change. This is unfortunate because some studies suggest that increased shipping emissions lead to large adverse health impacts, including 15,000–38,000 premature deaths per year and climate-related problems in East Asia (Liu *et al*. 2018; Fu *et al*. 2017).

The Hong Kong Special Administrative Region China (Hong Kong) has one of the top 10 international container ports in the world and has been proactive in reducing shipping emissions in the past decade. The Ocean Going Vessels Fuel at Berth regulation, implemented since July 2015 in Hong Kong, is the first marine fuel control regulation for ocean-going vessels in Asia. The key part of this regulation has been adopted nationally by China for the establishment of three domestic emission

BOX 3.6: BRICK KILNS IN NEPAL

A sharp increase in demand for building materials followed the earthquake that struck Nepal in 2015. To respond to this growing demand in a manner that reduced the harmful environmental and health impacts of brick kilns, the International Centre for Integrated Mountain Development (ICIMOD) collaborated with the Federation of Nepalese Brick Industry and MinErgy. The collaboration resulted in a manual for induced draught and natural draught zig-zag kilns that proposed modest changes to kiln design at a reasonable cost of about US$ 100,000 per kiln; free engineering support and a pay-back period of less than two years helped to make those costs acceptable. The nine newly designed kilns have delivered on their promise, effecting a 60 per cent decrease in particulate matter and a 40–50 per cent reduction in coal consumption, and increasing the proportion of high-quality A-grade bricks to 90 per cent of production. Brick kiln entrepreneurs from many parts of Nepal and other countries including Bangladesh, Pakistan and India are visiting the new kilns with an eye to carrying forward some of the lessons learned (Pradhan *et al*. 2018).

control areas (DECAs) in its coastal waters that will come into force in 2019. The latest estimates suggest that without control measures, both sulphur dioxide (SO_2) and particulate emissions are expected to increase by 15–61 per cent in the three DECAs in China between 2013 and 2020 (HKEPD 2011).

3.3.7 Solvents in industries and refineries

A set of industries that has received growing attention over concerns about air pollution emissions involves the production and use of paints, cosmetics, rubber and chemicals as well as cleaning in industry and households. In some parts of Asia and the Pacific, the use of solvents is overtaking the transport and industrial sectors as the largest source of volatile organic compounds (VOCs) (Wei *et al*. 2011). The sharp increase in the use of these substances has led some to call for a greater effort to target solvents in air pollution policies. Recent efforts have followed from the targets in China's 2013 Action Plan for Air Pollution Prevention and Control (Box 3.7). Delhi's government is aggressively pushing for the installation of vapour recovery systems at petrol pumps to reduce VOC emissions: by 2017, about 60 per cent of stations had been fitted with systems that not only reduce VOC emissions but save fuel. Illustrating a different regulatory style, Japan's authorities worked with industrial associations to design voluntary programmes that led to declines in VOC emissions from several key industries (Matsumoto *et al*. 2015).

3.4 DEVELOPMENT PRIORITY MEASURES

Although the implementation of conventional and next-stage policies to prevent air pollution will provide significant health benefits, the additional development priority measures identified could reduce population exposure to $PM_{2.5}$ by up to 60 per cent by 2030 relative to 2015. One billion people, about 22 per cent of Asia's population, could enjoy air quality that conforms to the WHO Guideline for $PM_{2.5}$ of 10 micrograms per cubic metre ($\mu g/m^3$), compared to only 8 per cent in 2015. Additionally, the number of people exposed to pollution above WHO's first Interim Target, which is the highest level, would decline by 80 per cent, from 2.3 billion in 2015 to 430 million in 2030. The development priority measures offer further means of improving air quality, even if they are not primarily targeted at air pollution. Often, they fall under the jurisdiction of different authorities in areas such as energy, agriculture or transport.

BOX 3.7: CONTROLLING EMISSIONS OF VOLATILE ORGANIC COMPOUNDS IN THE BEIJING-TIANJIN-HEBEI REGION

In China, VOC control gained momentum when the 2013 Action Plan for Pollution Prevention and Control was adopted, mandating provinces to prepare local action plans. As part of the region with the most stringent reduction targets, Hebei Province released their Action Plan Implementation Scheme for 2013–2017. Also in 2013, the Ministry of Environmental Protection issued a VOC Pollution Prevention Policy that required comprehensive control of VOCs in various industries. The application of leak detection and repair (LDAR) systems in the petrochemical industry exemplified one such response. A year later, the national government issued the Comprehensive VOC Control Policy in Petrochemical Industry, requiring industries to achieve a 30 per cent reduction in VOC emissions by 2017 relative to 2014. Then in 2015, the government introduced VOC discharge fees for the petrochemical, packaging and printing industries; Hebei Province and Beijing were among the 15 provinces and municipalities involved in the pilot. By the end of 2015, LDAR technology could be found throughout the petrochemical industry and incentives for VOC control were instituted for the Beijing-Tianjin-Hebei region. By 2017, Beijing successfully cut VOC emissions by 13,700 tonnes (exceeding their 13,500 tonne target), while Tianjin implemented online VOC emission monitoring of 19 key enterprises and 84 discharge outlets.

3.4.1 Clean cooking, heating and lighting

The implementation of measures to control emissions from indoor solid-fuel stoves, kerosene lamps and heating is a development priority for many countries

In several parts of Asia and the Pacific, residential stoves burn firewood, animal dung and other biomass for heating and cooking, while inefficient kerosene lamps often provide lighting in energy-poor regions. The unevenness of the fuels' combustion coupled with poor ventilation generates indoor air pollution. About 64 per cent of the world's population cook with solid fuels and the stoves contribute to at least 1 million deaths per year. Moreover, since seven of the top 10 population groups using solid fuels for cooking come from Asia and the Pacific, the impacts tend to be especially high in the region (WHO 2016). This is particularly the case for women and children, who spend more time near cooking environments (Rehfuess *et al*. 2006). Air quality and thermal efficiency can both be improved by stoves that use LPG or electricity and those equipped with fan-assisted technology – some of the numerous options across Asia, with an equally diverse range of performance. On balance, clean cookstoves can contribute to achieving many of the SDGs (Box 3.8).

The country that has received the greatest attention for its national cookstove programme is China. From the late 1970s to the early 1990s, several Chinese government agencies collaborated on the National Improved Stove Program (NISP) to bring cleaner stoves to 129 million households, reaching approximately 65 per cent of China's population. The programme benefited from the sustained effort of the Ministry of Agriculture and the discretion of other agencies to identify locally relevant solutions. This flexibility allowed agencies to start small and build to scale, and rural energy companies to create markets for improved products (Sinton *et al*. 2004; Smith *et al*. 2003). In 2007, for example, the Chinese government launched the One Solar Cooker and One Biomass Stove Program specifically in Tibetan regions and distributed 79,833 biomass stoves and 244,474 solar cookers over four years (World Bank 2013). While the NISP often gave the programme favorable reviews, others have suggested it achieved little improvement in indoor air quality, as other unimproved cookstoves were often also present in the kitchen (Edwards *et al*. 2007). China's cookstove programme has more recently undergone reforms, with new technologies, better programme oversight and stronger links to overarching development policies (Smith and Deng 2010). Starting in 2017, China's government mandated that residents replace coal stoves with furnaces burning natural gas. As there was a shortage in supply of natural gas, however, some families were left without heating in the winter, suggesting the importance of allowing sufficient time for the market to prepare for transition (Myers 2018).

India has also introduced several cookstove programmes to help the approximately 100 million (out of 240 million) households that lack access to modern cooking options. These efforts began with the National Programme for Improved Chulhas (NPIC), a programme that in its most recent form, known as the National Biomass Cookstoves Initiative (NBCI), is focusing on developing and promoting efficient (including fan-assisted), cost-effective, durable and easy-to-use biomass cookstoves. Other recent high-profile initiatives include an ambitious scheme called *Pradhan Mantri Ujjwala Yojana*. India's Ministry of Petroleum and Natural Gas launched this initiative in 2016 and has facilitated access to 35 million LPG connections for 100 million energy-poor households. The scheme involves convening meetings or *Ujjwala Panchayats* that allow users to connect with each other,

BOX 3.8: CLEAN COOKING AND THE SUSTAINABLE DEVELOPMENT GOALS

Clean cooking measures sit at the nexus of multiple SDGs. Ensuring access to clean and affordable cooking can directly benefit SDG 1.1, which aims to halve extreme poverty by, for example, reducing household expenditure on energy and the time spent collecting solid fuels. This also benefits SDG 4 by ensuring that children have more time for education as well as fewer school days missed due to air-pollution-related illness. This similarly impacts SDG 5.5 on ensuring women's full and effective participation and equal opportunities for leadership, and SGD 5.3 on reducing violence against women. Clean cooking measures contribute directly to many health-related targets such as SGD 3.9, by reducing deaths from air pollution, and SDGs 3.2 and 3.4, by reducing preventable deaths among children under five years and premature mortality from non-communicable diseases. Many clean cooking solutions, such as expanding access to LPG, also contribute to SGD 7.1 on universal access to modern energy, SDG 11.1 on access to safe housing and upgrading slums, and to SDG 11.2, by reducing the environmental impact of cities. Reducing forest degradation from fuelwood collection also contributes to SDG 8 by decoupling economic growth from environmental degradation, and to SDG 15.2 on the sustainable management of forests.

Measures addressing methane (CH_4) emissions from agriculture, such as manure management and intermittent aeration of rice paddies, can also promote multiple SDGs. Such measures contribute directly to SDG 2.1 to double food production, and to SDGs 2.2 and 2.3 to end hunger and malnutrition, by reducing the production of tropospheric ozone (O_3) which can suppress agricultural production and alter the nutritional value of some crops. Improvements in crop and forage production can also improve the economic livelihoods of farmers and herders, thereby furthering SDG 1.1. Such measures can also contribute to SDG 2.4 by improving sustainable agricultural production. Manure management measures, which recover CH_4 for further use, contribute to SDG 7.1 on ensuring universal access to modern energy. This can support SDG 1.1 by providing a cost-effective source of renewable energy to poor farmers and herders, and SDG 8 by decoupling economic growth from environmental degradation. Reducing fugitive CH_4 emissions in the agricultural sector also directly contributes to SDG 12.4, which aims to achieve environmentally sound management of all wastes.

eliciting their concerns and experiences and sharing information on LPG use and safety. Other smaller-scale activities in India have sought to extract indigenous knowledge and customize cookstoves to user needs (World Bank 2011a). Although the cases above focus on China and India, many other countries in Asia have accrued useful experiences arriving at a cookstove strategy (Box 3.9).

Programmes to reduce indoor sources of air pollution have largely focused on replacing the stoves and fuels used for cooking. However, in many places around the world, wood, coal and other biomass are used for home heating as well. In some developed countries, residential wood-burning stoves are common and subject to regulation and design guidelines, leading to relatively low emissions. However, heating stoves that burn coal are often used in places where coal is readily available, such as China and Mongolia (Stoves Summit 2017), and are typically older, inefficient and unregulated, with the exception of some urban areas that have introduced bans on the use of solid fuel for residential heating.

Globally, many stoves that are now considered cookstoves or heating stoves are actually used for both purposes, especially in the winter or in high-latitude or high-altitude regions where there is a greater need for space heating. Combined cooking and heating stoves may be particularly important since they are regularly used for long periods of time, such as overnight for heating, as well as for two or three discrete cooking events per day. These stoves are also often used in colder climates and at higher elevations, in close proximity to snow- and ice-covered regions. In these areas, even lighter-coloured combustion particles can reduce the reflectivity of the underlying surface, causing a warming influence on the climate. The 2017 Stoves Summit sponsored by the Climate and Clean Air Coalition (CCAC), International Cryosphere Climate Initiative, Global Alliance for Clean Cookstoves and Poland's Ministry of Environment, identified several mitigation opportunities for coal heating stoves and combined cooking and heating stoves. These solutions include emissions standards, testing and labelling; ecolabelling; technology development towards advanced low-emission stoves; fuel switching; district heating; upgrading biofuels and transition to pellet stoves; improving household energy efficiency; separating cooking and heating appliances/fuels; stove replacement programmes; policy and regulatory instruments; and financing options (Stoves Summit 2017).

BOX 3.9: CAMBODIA'S SUSTAINABLE GREEN FUEL ENTERPRISE

In common with many other countries in Asia, Cambodia has struggled with deforestation to provide wood for highly polluting residential stoves. The Sustainable Green Fuel Enterprise (SGFE) programme was initiated to develop energy-efficient cooking solutions and curb harmful environmental impacts. The SGFE is a private limited company that manufactures char-briquettes – made of 100 per cent recycled organic biomass waste – as a viable alternative to wood charcoal. With support from a Global Alliance for Clean Cookstoves Pilot Innovation Fund grant, the SGFE has grown significantly, producing 40 tonnes of char-briquettes per month, and providing a sustainable supply of clean fuel to approximately 500 households and small businesses. This growth is due to many factors, including financial management assistance from a tax consulting company; a new accounting system; improved gender relations and human resources management; in-kind support to conduct a fuel life-cycle assessment; and improved supply-chain management.

3.4.2 Clean energy

Policies that encourage the use of renewable energy and energy-efficient technologies can reduce energy consumption and improve air quality

The adoption of policies that encourage the use of renewable energy and energy-efficient technologies can reduce energy consumption and air pollution at the same time. Many countries in the region have adopted promotional policies – from renewable portfolio standards to feed-in tariffs – that have contributed to declines in the costs and increases in the consumption of solar and wind power (IEA 2016b) (Figure 3.4). The clearest example is China, where solar power consumption reached 28 terawatt hours (TWh) and wind power consumption reached 55 TWh in 2016, respectively constituting 36 per cent and 42 per cent of the global totals for these sources of energy (BP 2017). The declining costs and increased consumption of solar and wind power seem primed to continue in India, Indonesia, Japan, the Philippines, Thailand and other parts of the region (BNEF 2017). Some of this progress is attributable to forward-looking policies: India's 2006 National Environment Policy suggested an integrated approach, addressing energy conservation and the adoption of renewable energy technologies along with pollution abatement and strengthened monitoring and enforcement of emissions standards for different sources (MoEF 2006). However, growth in clean energy consumption and energy efficiency may also be due to reasons beyond proactive national governments.

3.4.3 Energy efficiency standards – households and industry

Energy efficiency standards for households and industry often pay for themselves over the lifetime of an investment. This potential has been recognized by the Chinese government, as illustrated by the inclusion of ambitious energy efficiency targets in its 11th, 12th and 13th Five-Year Plans. China has also introduced an energy efficiency programme that initially relied on a series of training, auditing and better reporting measures to improve energy efficiency in the country's 1,000 most energy-intensive industries. This programme was later expanded to encompass the top 10,000 most energy-intensive industries, with more responsibilities delegated to sub-national provincial governments to support training and reporting (Zhao *et al.* 2014).

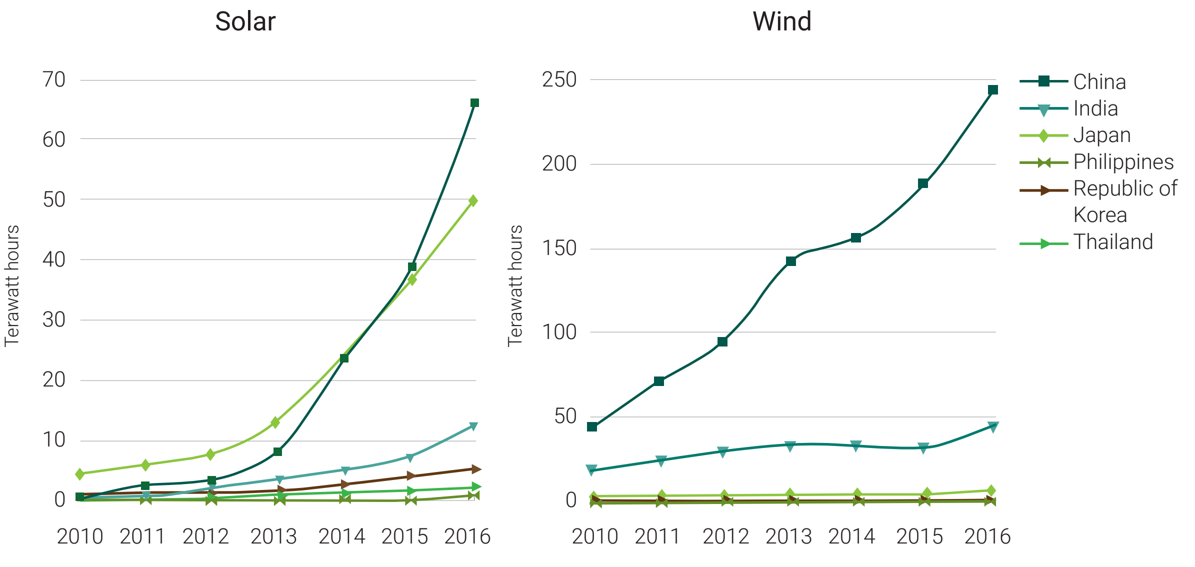


FIGURE 3.4: TRENDS IN SOLAR- AND WIND-POWERED ELECTRICITY GENERATION IN SELECTED COUNTRIES OF ASIA AND THE PACIFIC

India too has been proactive on energy efficiency. Under the Energy Conservation Act 2001, India established the Bureau of Energy Efficiency (BEE) to advance the energy conservation and efficiency agenda through a variety of mechanisms. For households, the BEE has implemented a labelling programme for appliances to provide informed choice to the consumer about a device's energy consumption. Labels are mandatory, so appliances such as air conditioners, for example, cannot be sold without an approved energy information label (BEE 2018).

Across Asia and the Pacific, there have also been attempts to introduce pre-paid cards for energy that can raise household awareness of energy use and motivate residents to purchase energy-efficient appliances. In the Republic of Korea, for instance, Seoul's metropolitan government introduced a variety of demand-driven energy-saving measures that also improve urban air quality as part of the One Less Nuclear Power Plant project (Lee *et al*. 2017; SMG 2017) (Box 3.10).

3.4.4 Improved public transport

Many developed countries in the Asia and Pacific region have relatively well-developed public transport systems that help reduce demand for personal transport. Often these systems are most effective when combined with other measures that discourage the purchase of motor vehicles. Singapore has received the most attention in this regard owing to its carefully designed transport demand-management strategy that charges cars for entering key parts of the city. Even smaller cities have enjoyed success in combining public transport with urban planning (Rye 2016). The city of Toyama, Japan, for example, sought to counter a rising trend in residents moving outside the city. To bring people back, the city invested considerable effort in making the city more compact and introducing a tram system that stops in its mixed land-use areas (Takami and Hatoyama 2008).

3.4.5 Electric vehicles

China has been a global leader in the supply of and demand for electric vehicles. This position is partially attributable to a deliberate move by the government to provide subsidies for the purchase of electric vehicles and remove driving restrictions based on licence plates in some cities (Du and Ouyang 2017). The government of India is also aggressively promoting the introduction of electric vehicles. Meanwhile, the city of Shimla has introduced some electric buses for commercial use. There have also been efforts in the private sector, with Ola launching a pilot scheme in the city of Nagpur to operate a multi-modal electric fleet (UITP-India 2018).

BOX 3.10: ENERGY – ONE LESS NUCLEAR POWER PLANT

Beginning in May 2012, the Seoul metropolitan government (SMG) introduced a project entitled One Less Nuclear Power Plant that aimed to reduce annual energy consumption by 2 million tonnes of oil equivalent – a reduction on a par with one nuclear power plant – by December 2014. The goal was to be achieved through the development of energy-self-sufficient villages, solar photovoltaic (PV) power plants, a cooperative power plants project, car-sharing systems and other small-scale innovations. The SMG encouraged the private sector to establish installations for PV generation as well as other fuel-cell and small-scale hydropower plants. The project owed its success to diverse groups of citizens actively participating in the implementation of community-based energy conservation programmes. The end result of this collaboration was that the project reached its energy savings goal six months ahead of schedule and the average annual power consumption of Seoul decreased by 1.4 per cent in 2013 in contrast to average increases of 1.76 per cent across the country.

Source: Lee *et al*. 2017; SMG 2017

3.4.6 Solid waste management

The Asia and Pacific region is home to a diverse range of waste management technologies and practices, so it is virtually impossible to identify a single solution. On balance, the region's developed countries tend to employ more advanced technologies such as incineration with energy recovery (waste-to-energy technology) and systematic recycling of recyclable materials. In contrast, developing countries tend to rely more on direct landfill, often associated with open – and sometimes illegal – dumping and burning, and informal recycling as well as environmentally sound intermediate treatment.

The cross-national differences in approaches to waste management appear at different junctures in the waste stream, starting with the transport of waste. Advanced economies such as Australia, Japan, the Republic of Korea and Singapore deploy technology-oriented solutions for waste collection and transport, including motorized vehicles, compactors and transfer stations, along with source separation and collection of recyclable wastes. Emerging economies such as Indonesia, Malaysia and Thailand also operate systematic collection and transport of wastes, at least in large cities, but collection of recyclables is still often informal or through community-based approaches such as waste banks.

Regional variations are also apparent in the treatment of waste. Cambodia, for example, has one engineered landfill site and 72 open dumpsites. Singapore recycles 59 per cent of its collected waste, of which it incinerates 39 per cent. Meanwhile, sanitary or engineered landfill treatment is commonplace in China and Japan. Further, Japan relies heavily on incineration (often with energy recovery) for intermediate treatment to reduce waste volumes. Malaysia utilizes eight engineered landfill sites and 165 controlled dumpsites. In Indonesia, more than 9 per cent of collected waste is disposed of at engineered landfill sites, almost 70 per cent by controlled dumping, and 3 per cent by open dumping.

Recycling in developing economies is often associated with large informal sectors. Although some efforts promote recycling as government policy, market-based and often informal recycling is very common in Bangladesh, Cambodia, China, India, Indonesia, Philippines and Thailand. Thus, one way to promote systematic recycling in the region is to collaborate with the informal sector. Systematic efforts to promote recycling vary greatly across the region: 83.4 per cent of all waste is recycled in the Republic of Korea, whereas just 5 per cent is recycled in Malaysia. Due to higher percentages of organic waste in the overall waste mix in low- and middle-income countries and the greater role of agriculture, the biological treatment of waste, such as composting and anaerobic digestion, is correspondingly more common. At the same time, low-income countries generally have a greater need for waste management infrastructure, technology and financing.

For much of Asia and the Pacific, burning is a relatively easy and low-cost way to dispose of waste. The practice is common among households with limited access to waste management facilities and also occurs in communities with rudimentary landfill sites prone to spontaneous combustion. Many parts of the region have introduced laws that forbid waste burning, imposing fines and penalties on those caught doing it; the Philippines' Ecological Solid Waste Management Act, for example, includes such provisions. At the same time, awareness and enforcement of legal prohibitions are often limited or altogether lacking. Not surprisingly, the most effective solutions tend to combine technical measures with awareness raising. To illustrate, Fiji has adopted a reduce, reuse, recycle awareness programme that has reduced both the quantity of waste generated and the amount of burning. More generally, the Pacific islands have begun to work together to develop regional strategies to enhance waste management and reduce the need for burning (Isley and Taylor 2018).

3.4.7 Rice paddies

Anaerobic fermentation of organic matter in flooded rice paddies generates CH_4, a process that can be interrupted by the drainage and intermittent aeration of paddies during the growing season. Many of Asia's farmers have adopted the practice to help save water and boost crop yields, achieving

BOX 3.11: WASTE MANAGEMENT IN THE PACIFIC ISLANDS AND SMALL ISLAND DEVELOPING STATES

Because the Pacific islands and Small Island Developing States (SIDS) are highly dependent on biological resources and ecosystems, managing waste is essential to safeguarding what are often pristine environments. The Pacific islands and SIDS employ relatively similar approaches to waste management. Regular waste collection services are concentrated in urban areas; reaching remote rural areas often presents a significant challenge. The SIDS rely chiefly on temporary dumpsites, open or controlled dumps, and sanitary landfills for municipal solid waste disposal. General waste, often mixed with hazardous wastes including health-care waste, can be burned or buried at the disposal site in the absence of incinerators. Waste picking and open burning is common, due, in part, to the limited waste collection services. Many SIDS are exploring municipal waste-to-energy options but would need enhanced capacity to properly manage the hazardous waste – such as bottom ash, fly ash and flue gas – that can result from these processes (SPREP 2016).

The Pacific Regional Waste Management and Pollution Control Strategy 2016–2025 (Cleaner Pacific 2025) is a comprehensive long-term strategy for the region to achieve sustainable waste management and pollution prevention (SPREP 2016). Cleaner Pacific 2025 has three key elements: addressing solid, liquid and hazardous wastes from varied sources, including disasters, asbestos, e-waste, health-care waste, used oil, trade, sewage and animals; chemicals management including persistent organic pollutants (POPs), mercury and O_3-depleting substances; and marine and terrestrial pollution control. Continuing support from regional projects and initiatives such as PacWaste and J-PRISM complement the achievement of the Cleaner Pacific 2025 goals.

- *Pacific Hazardous Waste Management Project – PacWaste Plus*. Following on the achievements of PacWaste, the 11th European Development Fund of the European Union has provided another EUR 17 million to fund PacWaste Plus to support the implementation of Cleaner Pacific 2025 in accord with similar regional initiatives. A four-year project amounting to EUR 7.85 million, PacWaste aimed to assist 14 Pacific islands and Timor Leste in managing hazardous health-care waste, asbestos, e-waste and atoll waste. Some of its key outputs include completing comprehensive regional baseline studies in 15 countries and 26 separate islands and improving physical structures and services for waste management, including health-care waste incinerators, asbestos remediation, e-waste interventions and waste collection services.

- *Japanese Technical Cooperation Project for Promotion of Regional Initiative on Solid Waste Management, Phase II (J-PRISM II)*. J-PRISM II supports the Cleaner Pacific 2025 strategic goals with funding from the Japan International Cooperation Agency (JICA). Phase II will focus on developing a monitoring mechanism for tracking the progress of solid waste management. The project is running from February 2017 to 2022 in eight countries as well as the Cook Islands, Nauru and Niue.

Source: SPREP 2017; SPREP 2016; Agamuthu and Heart 2014 reductions in CH_4 emissions as a desirable side effect (Wassmann *et al*. 2009).

Due to a variety of successfully demonstrated approaches in the region, the goal is frequently to spread the word about successful options rather than initiate new drainage schemes. In Japan, farmers have adopted the practice of draining their rice paddies for 10 days in the middle of the growing season to increase crop yields (Nagata 2010). China has experienced a more recent and dramatic embracing of drainage: between 1980 and 2000, the percentage of farmers using the practice rose from approximately 25 per cent to 80 per cent (Li 2002). A system of rice intensification that incorporates intermittent drainage alongside resource-conserving planting and soil and nutrient management suggests that multiple elements combined together may be useful for improved food security and CH_4 emission reductions (Uphoff 2007).

3.4.8 Wastewater treatment

It is estimated that globally wastewater emitted approximately 512 million tonnes of CH_4 in 2010, accounting for approximately 7 per cent of total CH_4 emissions. Emissions from wastewater are expected to grow by about 19 per cent between 2010 and 2030 (GMI 2013b).

Inadequate wastewater systems are a significant cause of CH_4 emissions in Asia and the Pacific. As Asia's population and economies continue to grow, the region's demand for water will increase significantly. Accelerated urbanization and changing consumption patterns, including diets shifting towards highly water-intensive foods such as meat, are also contributing to this increasing demand (WWAP 2017).

Wastewater from human activities and agricultural operations and its overall pollution load will also grow significantly in the region. Due to a lack of water infrastructure and technical, institutional and financial capacity, especially in developing countries, around 85–89 per cent of Asia's domestic wastewater is discharged directly into nearby water bodies without treatment, causing severe contamination to both surface and groundwater (Bao and Kuyama 2013). The need to deal collectively with pollution caused by untreated wastewater discharge is therefore urgent. At the same time, in the face of growing water demand, wastewater is gaining momentum as a reliable resource, shifting the paradigm of wastewater management from treatment and disposal to reuse and recycling, and particularly to resource recovery – for example biogas (WWAP 2017).

In most developed countries, centralized aerobic wastewater treatment systems are commonly used to treat municipal wastewater. These systems produce small amounts of CH_4 emissions, but also large amounts of biosolids that can significantly increase the emissions. Meanwhile, in developing countries with low rates of wastewater treatment, the systems that do exist tend to be low-cost and less energy-intensive, utilizing the process of anaerobic digestion of organic matter and resulting in greater biogas emissions. This biogas, a proven and widely used source of energy in Asia, is a mixture of CH_4 (55–75 per cent) and carbon dioxide (CO_2) (25–45 per cent) (Demirbas *et al*. 2016).

A number of proven technological approaches to methane mitigation and recovery at wastewater treatment plants have been applied successfully in developed countries (Table 3.2). Typical systems include biogas digesters on a small and medium scale, lagoon systems, medium- and large-scale anaerobic digesters, septic tanks and other type of latrines. Successful applications of anaerobic digestion have been reported around the world, including in Asia (GMI 2013b). The technology is widely used in treating livestock manure and sewage sludge.

Although biogas is a clean and renewable energy and considered an alternative to fossil fuels, its dissemination is still limited and it is mainly used by small-scale farmers in Asia and the Pacific. One of the major constraints is a lack of financial attractiveness. Even top-rated biogas-producing countries provide governmental and non-governmental subsidies. Thus, in order to ensure the sustainability of this technology, existing policies should reform subsidies, motivate investors with favourable financial conditions, and involve farmers early and often in local projects (Yousuf *et al*. 2017).

TABLE 3.2: WASTEWATER MANAGEMENT SOLUTIONS

Technical options	Description
Installing anaerobic sludge digesters (new construction or retrofit of existing aerobic treatment systems)	Anaerobic digesters are used to process wastewater biosolids and produce biogas, which can be used on site to offset the use of conventional fuel that would otherwise be used to produce electricity and thermal energy.
Installing biogas capture systems at existing open-air anaerobic lagoons	Biogas capture systems for anaerobic lagoons are the simplest and easiest method of harnessing wastewater biogas. Rather than investing in a new centralized aerobic treatment plant, covering an existing lagoon and capturing the biogas can be the most economically feasible means of reducing CH_4 emissions.
Installing new centralized aerobic treatment facilities or covered lagoons	Installing new centralized aerobic treatment systems or new covered lagoons to treat wastewater in place of less-advanced decentralized treatment options (or no treatment at all) can greatly reduce current and future CH_4 emissions associated with wastewater. This option is most viable in areas with expanding populations that have the infrastructure and energy available to support such systems.
Installing simple degassing devices at the effluent discharge of anaerobic municipal reactors	In several developing countries with warm climates (e.g., Brazil, India, Mexico), anaerobic reactors fed directly with municipal wastewater – e.g., upflow anaerobic sludge blankets (UASBs), anaerobic filters, and fluidized or expanded bed, baffled reactors – are increasingly being used for small- and medium-scale municipal wastewater treatment. In these systems, around 30 per cent of the CH_4 produced is lost as dissolved gas in the treated effluent. A closed column with enough turbulence right after the reactor can capture a significant amount of $CH_{4,}$ which may be used beneficially or directed to a flare.
Optimizing existing facilities/systems that are not being operated correctly and implementing proper operation and maintenance	Optimizing existing facilities and wastewater systems that are not being operated correctly to mitigate CH_4 emissions is a viable alternative to installing new facilities or wastewater treatment processes such as anaerobic digesters. Proper operation and maintenance also ensure that facilities continue to operate efficiently, with minimal CH_4 emissions.

3.4.9 Oil and gas

Methane emissions occur in all sectors of the oil and natural gas industry, from production through processing to transmission, and result from normal operations and routine maintenance as well as fugitive leaks and system upsets.

As oil or gas moves through the system, emissions occur through both intentional venting and unintentional leaks. Venting can occur through equipment design or operational practices, such as the continuous bleed of gas from pneumatic devices that control gas flows, levels, temperatures, and pressures in the equipment, or from well completions during production.

In addition to vented emissions, CH_4 losses can occur from leaks (also referred to as fugitive emissions) in all parts of the infrastructure, from connections between pipes and vessels, to valves and equipment (US EPA 2017).

Methane emissions can also occur from the oil industry as a result of:

- field production operations: venting of associated gas from oil wells and storage tanks;
- production-related equipment: gas dehydrators, pig traps and pneumatic devices.

Numerous technologies exist to control emissions and their costs have been summarized (US EPA 2017b). The potential of these technologies is illustrated in Figure 3.5. Analyses of the top 10 opportunities to capture unintended and unnecessary CH_4 emissions from oil and gas production, including shale gas, show that they could reduce CH_4 emissions by more than 80 per cent and generate US$ 2 billion in additional revenue for the industry in the United States each year (NRDC 2012). These technologies have huge implications for global CH_4 emission reductions.

The oil and gas industry understands the need to reduce CH_4 emissions. In India, for example, a flare gas recovery system was installed to help recycle and recover flare gases that are piped in from Mumbai High offshore field (Emam 2015). Meanwhile, Indonesia has adopted a zero flaring policy as part of its climate change strategy (UKP4 2011). In 2017, eight of the world's largest oil and gas companies agreed to act to reduce CH_4 emissions, with BP, Total, ExxonMobil, Royal Dutch and four others agreeing to implement guiding principles to minimize leaks from energy infrastructure (Financial Times 2017).

3.4.10 Coal mining

Methane can be released into the atmosphere during the process of mining coal. The amount of CH_4 released by this activity is predicted to increase sharply in Asia and the Pacific due to enhanced productivity of mining techniques and the extraction of more coal from deeper, gassier seams. Rather than releasing the CH_4 into the atmosphere, it is possible to capture and use it to generate energy, operate industrial boilers, or for other productive purposes. This can be accomplished with the installation of degasification systems that capture it. In some cases, enhanced degasification systems are needed to capture CH_4 that has been diluted with air (known as ventilated air CH_4) to safeguard against mine outbursts and explosions. While it is common for mines in developed countries to have recovery systems, the high upfront costs of investing in the necessary technologies has made

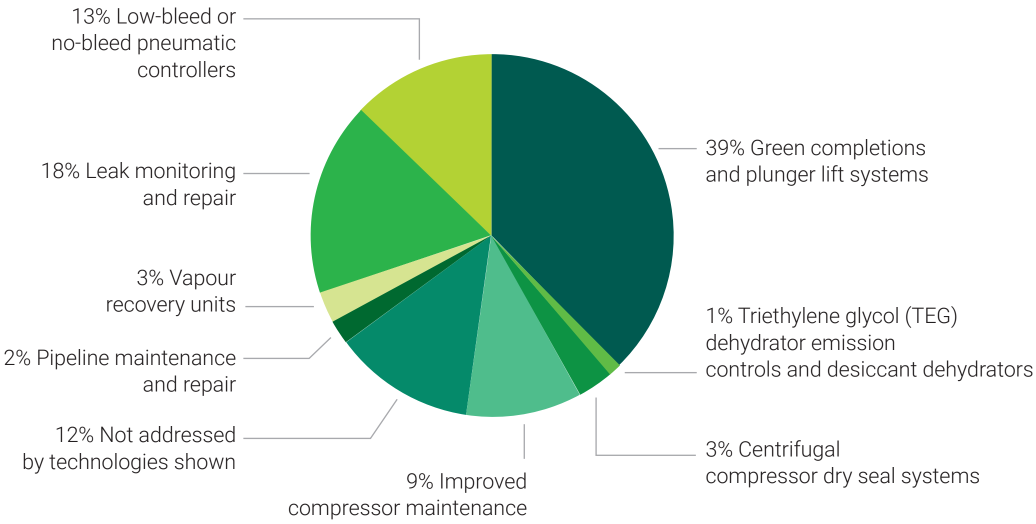


FIGURE 3.5: TECHNOLOGIES WITH THE GREATEST POTENTIAL TO REDUCE METHANE EMISSIONS IN THE OIL AND GAS INDUSTRY

Source: NRDC 2012

it less common in developing countries. About a decade ago, China began to use resources from the Clean Development Mechanism (CDM) to overcome this barrier and facilitate the transfer of recovery technologies. Since then, it has adopted several other domestic enabling policies that have provided regulatory and financial incentives, such as tax relief, for investors in CH_4 recovery projects (Karacan *et al*. 2011; US EPA 2009).

3.4.11 Hydrofluorocarbons

Reductions in energy use and pollution emissions can be achieved with options that cut emissions of hydrofluorocarbons (HFCs). One such set of options involves retrofitting large and medium-sized facilities with refrigeration and air conditioning systems or other manufacturing processes that have low global warming potential (GWP) (Carvalho *et al*. 2014). These changes are under way in Indonesia, with a large group of Alfamidi convenience stores having installed energy-saving refrigeration systems (Box 3.12). Yet another positive sign involves India's appliance manufacturer, Godrej & Boyce, which leapfrogged high-GWP HFCs and went directly to lower-GWP alternatives, selling more than 100,000 HC-290 room units with support from the German Development Agency and India's Ministry of Environment (NRDC *et al*. 2014). As the majority of Asia imports HFC products, policy makers and standard-setting organizations need clear market signals to avoid the accumulation and dumping of HFC technologies. Japan's Revised Fluorocarbons Recovery and Destruction Law, enacted in 2013 and entering into force in 2015, offers a clear signal with measures that require manufacturers to dispose of gases as well as regulate the products that use them (Kumakura 2015).

3.4.12 Sub-regional priorities

As noted in Chapter 2, there are several measures that are not part of the top 25 measures at the regional level, but which could lead to significant reductions in pollutant emissions in sub-regions or particular countries. For instance, in Bangladesh the government has identified rice-parboiling units as an important source of air pollution and introduced remedial measures to curb emissions.

3.4.13 Air pollution episodes

In response to episodes of high concentrations of air pollution that attract considerable public attention, governments in Asia and the Pacific are increasingly aiming for short-term interventions that should either reduce the severity of an envisaged pollution episode or minimize the exposure of people to polluted air during these episodes.

Most pollution episodes are caused by high emissions across a large area upwind of cities and enhanced by unfavourable meteorological conditions, including low wind speeds and limited atmospheric mixing. The emissions responsible for the pollution – $PM_{2.5}$, SO_2 and nitrogen oxides (NO_x), amongst others – remain in the atmosphere for about a week. During that time, upwind emission sources contribute to

BOX 3.12: ENERGY-EFFICIENT REFRIGERATION IN INDONESIA

In an effort to conserve energy and reduce costs, Indonesia's Alfamidi convenience stores, operated by PT Midi Utama Indonesia, have, since 2014, introduced a CO_2 refrigeration system as standard for new stores. The new system's energy efficiency was 18 per cent higher than that of the conventional HCFC-22 systems, lowering costs and contributing to environmental benefits. Power consumption data taken at three stores in Jakarta from 1 April 2014 to 31 March 2015 showed the stores' average electricity saving to be 17,624 kilowatt hours (kWh) per year, corresponding to 12.9 tonnes of CO_2 per year per store, compared with the estimated power consumption of HCFC-22 refrigeration systems of a similar capacity (UNEP and CCAC 2014). As of August 2015, Alfamidi had installed CO_2 refrigeration systems at a total of 912 stores across Indonesia.

pollution in the target area. For a short-term action plan to be effective, emission controls need to begin about a week before the predicted event, and should cover upwind sources over a distance of up to 1,000 kilometres due to the low wind speeds typical of pollution episodes. Uncertainties about weather forecasts extend the emission control area.

Many techniques have been adopted to manage and mitigate the effects of these episodes. Some focus on raising awareness of the severity of air pollution and encouraging people who might be especially vulnerable to stay indoors. This can involve setting up alert systems and public communication plans. Other methods focus on temporary restrictions on vehicles and the halting of construction. Many of the above approaches were implemented in China following a series of heavy pollution episodes that attracted policy-maker attention in 2013 (Feng and Wenjie 2016). In Southeast Asia, these episodes frequently have a transboundary character, which has led to efforts to strengthen the ASEAN Transboundary Haze Agreement (Box 3.5).

Short-term policy interventions have been particularly successful in China, which has been able to achieve emission reductions over very large areas. In other cases, where governments have less capacity to impose temporary suspensions on a wide enough range of economic activities over a sufficiently large area, interventions have been less successful. In addition, given the disruptive nature of such interventions, the economic effectiveness of suspending activity remains questionable. Long-term strategies that reduce emissions from the most polluting activities in a planned and scheduled manner are considered more cost-effective than policies that repeatedly require the shut-down of entire production processes, restrict the mobility of people and goods, or reduce labour productivity.

3.5 GOVERNANCE AND FINANCE

The top 25 clean air measures for Asia and the Pacific offer a menu of options for governments to consider in their own national contexts. There is no uniformly applicable set of solutions, and priorities will differ across and within countries. Decision makers will therefore need to tailor selected options to their national circumstances. In addition, there is no set sequence a given country or community should follow. Decision makers may want to place a greater emphasis on agriculture then turn to industrial sources; or they may concentrate on transport before transitioning to fossil fuels. Though the priorities and their sequence are likely to vary from one country to the next, one of this report's main messages is that decision makers should aim to strengthen the scientific basis for their solutions (Figure 3.1). In so doing, they should be aware that all of the top 25 measures have been implemented with some level of success in the region. The solutions are grounded in both science and experience.

The next logical question is what were the factors behind the more successful experiences? Table 3.3 summarizes successful implementation and describes some important reasons behind it. Often, the factor leading to exemplary action was growing awareness of the magnitude and severity of air pollution – which again underlines the importance of building a sound scientific basis for decisions. The success factors also highlight the significant role of enabling policies – from regulatory standards to tax incentives – which created the conditions that made it easier to introduce the measures. Finally, the list of successful measures underlines the crucial role of how different stakeholders in and beyond the government introduced enabling policies, financial incentives and other resources to make implementation possible.

A persistent problem with environmental policies is that what is written on paper is often not implemented in practice, making a lack of compliance a significant hurdle to progress on air pollution prevention and control in much of Asia and the Pacific. Appropriate governance and financing arrangements can help overcome that hurdle and close longstanding implementation gaps. The next section concentrates on the kinds of governance and financial arrangements that could help implement a portfolio of different options.

TABLE 3.3 FACTORS ENABLING THE SUCCESS OF CLEAN AIR MEASURES IN ASIA AND THE PACIFIC

Regional application of conventional measures		**Relevant experiences/ case studies**	**Enabling/success factors**
Post-combustion controls	Introduce state-of-the-art end-of-pipe measures to reduce sulphur dioxide, nitrogen oxides and particulate emissions at power stations and in large-scale industry	Thailand's installation of flue gas desulphurization technologies	Tightening of standards based on health impact studies (WHO guidelines) that stimulate investment in pollution control/cleaner technologies
Industrial process emissions standards	Introduce advanced emissions standards in industries, e.g., iron and steel plants, cement factories, glass production, chemical industry, etc.	China's adoption of waste heat recovery technologies	Tightening of production, performance and emissions standards that stimulate investment in pollution control/cleaner technologies
Emissions standards for road vehicles	Strengthening all emissions standards; special focus on regulation of light- and heavy-duty diesel vehicles	Regional tightening and updating of mobile-source emissions standards	Collaboration between environmental agencies, transport agencies, oil companies and vehicle manufacturers
Vehicle inspection and maintenance	Enforce mandatory checks and repairs for vehicles	Tokyo's (Japan) diesel control strategy	Centralized inspection and maintenance systems developed through multi-agency collaboration; self-funding mechanism for regular audits at test centres
Dust control	Suppress construction and road dust; increase green areas	Bangladesh's (Rajhashi) tree-planting scheme	Forward-looking politician and general public support

TABLE 3.3 FACTORS ENABLING THE SUCCESS OF CLEAN AIR MEASURES IN ASIA AND THE PACIFIC (contd.)

Next-stage air quality measures that are not yet major components of clean air policies in many parts of Asia and the Pacific		**Relevant experiences/ case studies**	**Enabling/success factors**
Agricultural crop residues	Manage agricultural residues including strict enforcement of bans on open burning	Thailand's open burning controls	Growing policy-maker and public awareness of pollution sources/ impacts; complementing burning bans with other use options with the involvement of farmers, alternative off-site use of crop residues, technologies that plough residues into fields
Residential waste burning	Strictly enforce bans of open burning of household waste	The Republic of Korea's waste management policies	Regulation on engineered landfills and incineration; collaboration with informal sector for recycling
Prevention of forest and peatland fires	Prevent forest and peatland fires through improved forest, land and water management and fire prevention strategies	Indonesia's cooperation with Malaysia/Singapore	ASEAN Agreement on Transboundary Haze Pollution
Livestock manure management	Introduce covered storage and efficient application of manures; encourage anaerobic digestion	China's agricultural policies	Combination of regulation, policy and programmes for covering compost; incorporating manure into soil
Nitrogen fertilizer application	Efficient application, urease inhibitors, use of ammonium nitrate	Bangladesh's use of urea super granules	Changing to modified ammonium nitrate fertilizer; cost-benefit analysis of the efficient application of nitrogen fertilizer
Brick kilns	Improve efficiency and introduce emissions standards	Kathmandu's (Nepal) shift from bull trench to zig-zag kilns	Clear presentation of the benefits of the retrofit; collaboration with kiln owners and technical experts in the kiln redesign
International shipping	Require low-sulphur fuels and control of particulate emissions	Hong Kong's rules on port emissions	Support from the International Maritime Organization
Solvent use and refineries	Introduce low-solvent paints for industrial and do-it-yourself applications; leak detection; incineration and recovery	China's volatile organic compound control policy	Growing public concern over particulate pollution; comprehensive reduction targets

TABLE 3.3 FACTORS ENABLING THE SUCCESS OF CLEAN AIR MEASURES IN ASIA AND THE PACIFIC (contd.)

Measures contributing to development priority goals with benefits for air quality		Relevant experiences/ case studies	Enabling/success factors
Clean cooking and heating	Use clean fuels – electricity, natural gas, liquefied petroleum gas (LPG) in cities, and LPG and advanced biomass cooking and heating stoves in rural areas; substitution of coal by briquettes	China and India cooking and heating programmes	Growing policy-maker awareness of the impacts of cooking on health; lessons learned from the design of previous programmes
Renewables for power generation	Use incentives to foster extended use of wind, solar and hydro power for electricity generation and phase out the least efficient plants	China, India, Indonesia, Japan, Thailand, and the Philippines' renewable programmes Seoul's (Republic of Korea) One Less Nuclear Power Plant project	Including renewable power generation in energy and climate policies; public pressure to switch from fossil fuels and nuclear to renewables
Energy efficiency standards for households	Use incentives to improve energy efficiency of household appliances, buildings, lighting, heating and cooling; encourage roof-top solar installations	India's household energy programmes Australia's rooftop solar incentives	Creation of bureau of energy efficiency
Energy efficiency standards for industry	Introduce ambitious energy efficiency standards for industry	China's Five-Year Development Plans	Including energy efficiency targets in Five-Year Plans
Electric vehicles	Promote use of electric vehicles	Mongolia's excise tax that favours electric and hybrid vehicles	Policy that supports and promotes the use of electric vehicles
Improved public transport	Encourage a shift from private passenger vehicles to public transport	Japan's (Toyama) Compact City Planning	Integration with Compact City Planning
Solid waste management	Encourage centralized waste collection with source separation and treatment, including gas utilization	Pacific islands and Small Island Developing States' waste management	Regional waste management policy and strategy

TABLE 3.3 FACTORS ENABLING THE SUCCESS OF CLEAN AIR MEASURES IN ASIA AND THE PACIFIC (contd.)

Measures contributing to development priority goals with benefits for air quality		**Relevant experiences/ case studies**	**Enabling/success factors**
Rice paddies	Encourage intermittent aeration of continuously flooded paddies	Viet Nam's agricultural practices	Established tradition of irrigation and drainage policy
Wastewater treatment	Introduce well managed two-stage treatment with biogas recovery	Japan's treatment technologies	Promotion of decentralized wastewater treatment units
Coal mining	Encourage pre-mining recovery of coal mine gas	China's methane recovery programme	Use of existing economic incentives, tax; incentives, well-defined gas property rights unsubsidized free gas market education and information dissemination
Oil and gas production	Encourage recovery of associated petroleum gas; stop routine flaring; leakage control	India's flare gas recovery systems	Collective corporate action
Hydrofluorocarbon (HFC) refrigerant replacement	Ensure full compliance with the Kigali Amendment	Indonesia's HFC reduction policies	Government mandate to shift to low-GWP coolants; clear presentation of the cost savings from technology change

BOX 3.13: SUSTAINABLE DEVELOPMENT GOALS 16 AND 17 AND AIR POLLUTION

In 2015, the international community agreed on the SDGs to help guide a development transformation in all countries through to 2030. Air pollution is mentioned in three of the 169 targets – 3.9 on health; 11.6 on cities; and 12.4 on sustainable consumption and production – with many of the other SDGs also relevant to the drivers and impacts of air pollution (Elder and Zusman 2016). Though not as explicit, SDGs 16 and 17, which focus on governance and means of implementation, include many targets that could help improve air quality management. For SDG 16, these range from 16.3 on the rule of law to 16.6 on effective, accountable and transparent institutions. For SDG 17, they range from 17.1 on strengthening domestic resource mobilization to 17.7 on promoting the development and transfer to developing countries of environmentally sound technologies.

Multi-stakeholder partnerships can help improve compliance, delivering cleaner air and other benefits to Asia and the Pacific

3.5.1 Government agencies

The term governance refers to the exercise of authority in the pursuit of publicly desirable goals. The performance of national and local agencies is pivotal to successfully governing air pollution. As such, it is important to consider which authorities have the responsibility to govern – that is to rule and to control air quality and pollution. The existence of institutional capacity in terms of personnel and knowledge, paired with a clear political and legal mandate, are crucial for the successful implementation and control of air quality measures, and ultimately to establishing a link to further commitments at the international level, such as the SDGs.

Most countries in Asia and the Pacific have established air quality management agencies or divisions in environmental agencies. In Thailand, for example, the Pollution Control Department (PCD), founded in 1992 under the Ministry of Natural Resources and Environment, has the responsibility for preventing and controlling air pollution under the Enhancement and Conservation of National Environmental Quality Act (1992) (PCD n.d.). Many of these agencies have seen their staffing and budgets grow in recent years. For example, the number of employees working in sub-national environmental protection bureaus in China doubled between 1998 and 2014. These are promising trends that will need to continue – and be considerably strengthened for many countries – to achieve the goals presented in this report.

A concern closely related to capacity is whether environmental agencies have the *de facto* authority to regulate emission sources. Though environmental agencies have seen their status rise across Asia, they may struggle if more powerful agencies have conflicting objectives (Li 2006). Fortunately, however, there are also signs of changing agency power dynamics. The growing awareness of the adverse impacts of air pollution, for example, led to important institutional reforms in China. In 2015, China's government introduced a vertical management system at the Fifth Plenary Session of the 18th Central Committee Conference to help address several institutional issues that previously hampered compliance with air pollution regulations and policies.

Coordination across and within agencies is also becoming more essential. This is particularly the case because more integrated air pollution and climate change policies will require steadily strengthening coordination across government agencies to improve air quality, mitigate climate change and yield a range of other benefits. Examples of improved coordination include the decision for China's newly-created Ministry of Ecology and Environment (MEE) to absorb functions that were originally under other ministries, particularly climate change and emission reduction policies. Another illustration is the inclusion of air pollution in nationally determined contributions (NDCs) that have been pledged to the United Nations Framework Convention on Climate Change (UNFCCC).

Other considerations involve the devolution of authority to sub-national governments. Over the past two decades, governance has become multi-tiered or polycentric with power increasingly shared among different stakeholders outside central government (Andersson and Ostrom 2008; Bulkeley and Betsill 2005). Reflecting this redistribution of authority, cities have been delegated many new responsibilities over air pollution. While devolution or vertical integration can be problematic if local governments are lax or lack capacity, sub-national governments can also be an important source of innovation. This is clearly evident in the reforms to public transport and urban planning found throughout Asia and the Pacific. In some cases, central governments can encourage these innovations through fiscal policies that transfer resources or grants to help local governments finance new solutions to air pollution.

3.5.2 Civil society and the general public

Civil society and the general public are an increasingly important source of support for environmental policies and measures. Environmental movements that helped spur institutional change in developed countries during the 1970s have become notably more influential in advancing new approaches to environmental management in developing countries over the past two decades (Yang and Calhoun 2007; Mertig and Dunlap 2001; Mertig and Dunlap 1995; Dunlap and Mertig 1992). Countries are also setting up institutional channels allowing civil society organizations and the general public to articulate concerns about pollution (Jodoin *et al*. 2015). For example, Greenpeace East Asia is working actively from Beijing, Hong Kong, Seoul and Taipei in combating pollution and climate change (Greenpeace East Asia 2012). Recently, some governments also seek to improve the dialogue with societal groups and the general public by creating institutional channels through which concerns about pollution can be shared (Jodoin *et al*. 2015). In China, for example, public concerns can be articulated through complaint letters sent to environmental protection bureaus. Civil society organizations can also play an important role in monitoring pollution, serving as an early warning system that enhances capacities to monitor pollution sources (Cohen 1998). Thailand's Pollution Control Department, to cite another case, often inspects pollution sources based on citizens' complaints (AECEN 2004). A third case is the Philippines' creation of multipartite monitoring teams made up of a variety of stakeholders that help the government monitor projects (Environmental Management Bureau n.d.).

In some countries, notably Pacific island nations, community leaders outside formal government may have more influence on the behaviour of residents. Giving community leaders authority to enforce some directives, such as bans on burning domestic waste, agricultural waste or forests, has been more effective in Fiji than government directives (Isley and Taylor 2018).

Reliable, accurate and timely monitoring data – though not strictly an actor that exercises authority – can help improve compliance and strengthen regulatory authority. Most air quality monitoring stations measure PM_{10}, $PM_{2.5}$ and total suspended particulates. Coverage is typically more extensive in developed countries or the capital cities of developing ones. Most large cities in Japan, the Republic of Korea, Singapore and Thailand observe stringent monitoring procedures, but many other cities confront limits on equipment, monitoring and siting procedures, and quality assurance and control procedures (World Bank 2011b). India has recently made significant efforts to improve its National Air Quality Monitoring Programme (NAMP) – which began in 1984 and consists of close to 700 stations covering approximately 300 cities and towns. Additional finance can help improve monitoring in India and elsewhere, but careful thought is needed to ensure the sustainability of funding as aid-driven air quality monitoring programmes can cease operations once funding runs out (ADB and Clean Air Asia 2014).

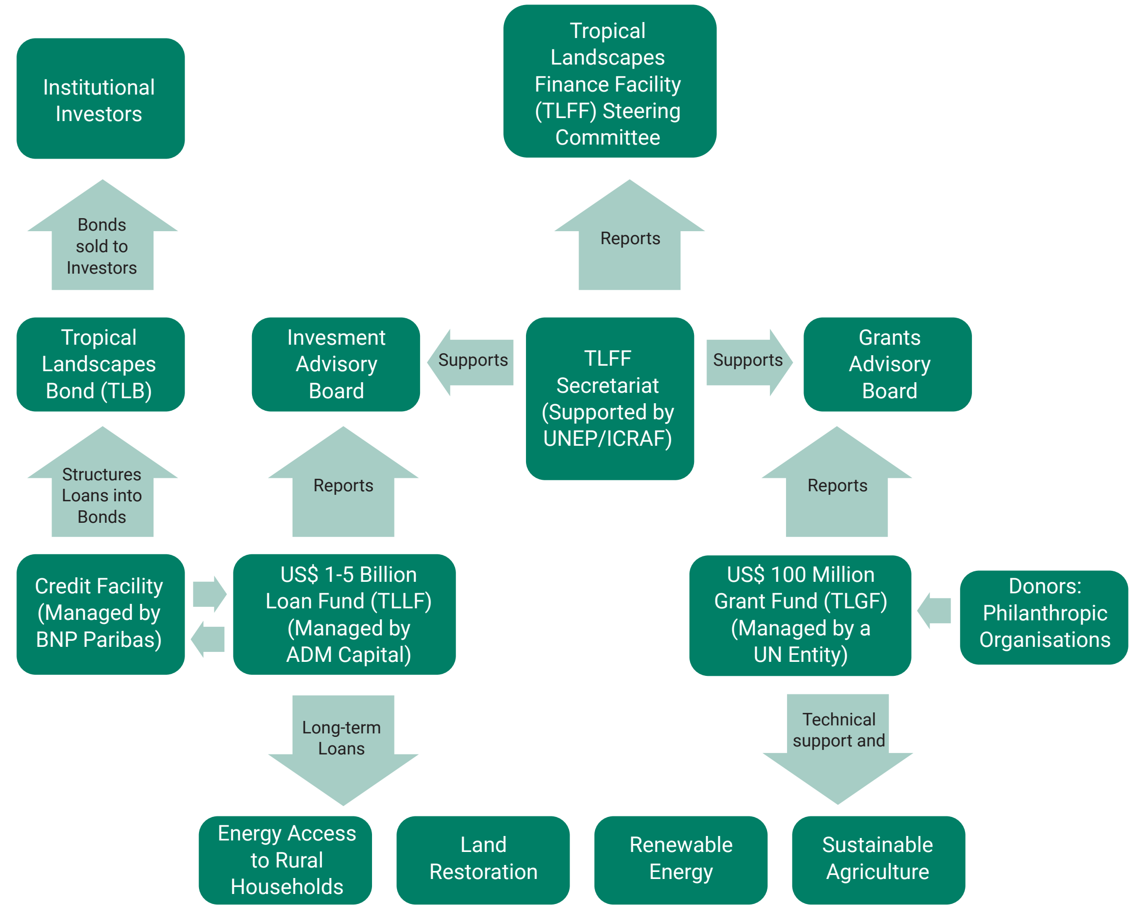
3.5.3 Funding

One of the main reasons behind gaps in compliance is the lack of financial resources for pollution prevention and control. Most countries in Asia allocate financial resources for environmental management as part of annual nationally appropriated funds. One way to boost those outlays is to ensure that urban planning prioritizes air pollution control measures – and hence the allocation of funds for the enforcement of such measures at the local level. Private-public partnerships can help support cleaner infrastructure. Special funds to finance air pollution control projects may also be established by governments. The Philippines set up the Special Vehicle Pollution Control Fund (SVPCF) as a seed fund to support emission reduction initiatives in the transport sector. Funds are generated from a charge on all motor vehicles, paid by the owner (Napalang *et al*. 2016).

The private sector, particularly financial institutions, can complement government efforts by supporting investments that reduce air pollutants (UNESCAP 2016). Several of the top 25 measures are consistent with national development priorities and could be supported from public funds. At the same time, the private sector and businesses can help fund cleaner technologies, provided a favourable enabling environment is in place. Currently, there are also a number of innovative instruments available to finance green projects (Box 3.15). Green bonds, which are estimated to increase to US$ 100 billion in 2018, can be a major source of finance. Commercial banks can be required to lend a certain percentage of their investment portfolio for green projects. This

BOX 3.14: TROPICAL LANDSCAPES FINANCE FACILITY – LEVERAGING PUBLIC FINANCE TO SUPPORT GREEN GROWTH

In line with the SDGs and the Paris Climate Agreement, the Indonesian government, together with UN Environment, the World Agroforestry Centre (ICRAF), BNP Paribas, and ADM Capital, officially launched the Tropical Landscapes Finance Facility (TLFF) on 26 October 2016. The TLFF, as the first private-sector landscape financing facility at scale, aims to pool financial resources for supporting sustainable agriculture and land management, renewable energy, and overall rural livelihoods. The TLFF mobilizes capital through its loan and grant funds. The TLFF Loan Fund seeks to provide long-term loans of at least 10 years' duaration to projects that comply with zero deforestation criteria and environmental, social and governance standards. The work to be undertaken by the TLFF Grant Fund focuses on capacity building of farmers and rural communities, land rehabilitation, and the availability of renewable energy in rural areas. This component provides an opportunity for institutions and philanthropic foundations to contribute to green growth and sustainable development in Indonesia.



Tropical Landscapes Finance Facility Operational Framework

Source: TLFF 2017

strategy was successfully implemented in Fiji, and even exceeded its targets (UNESCAP 2016). For some of the top 25 measures, it may also be possible for development banks working in the region to employ these instruments to help overcome such barriers as high upfront costs. In a similar way, development banks may consider aligning their strategies with some of the top 25 measures. Last but not least, there may be growing opportunities to tap climate finance mechanisms such as the Green Climate Fund for activities that prevent air pollution in mitigating greenhouse gases.

A final set of factors involves the role of business and industry. Polluting industries can assist or prevent changes in the design and implementation of regulations, particularly if they work with regulatory agencies who seek to change pollution-intensive development patterns. At the same time, businesses are recognizing the advantage of taking action to preserve the environment and investing in new energy and cleaner production technologies (King and Lenox 2002; Maynard and Shortle 2001; Wheeler 2000; Gunningham and Rees 1997; Porter and van der Linde 1995). This is especially true for publicly traded firms which fear that negative publicity around environmental neglect could deter stock-market investors (Mamingi *et al*. 2008; Dasgupta *et al*. 2001). Getting industries on board is accomplished most easily when the government and the public push for better industrial environmental performance and financial markets steer in the same direction. In such cases, industry has incentives to clean up, especially for financially viable enterprises that are targeting a global market or first-mover status in an emerging one (Esty and Winston 2009; Porter and van der Linde 1995).

3.5.4 International and regional agreements

There is currently no global treaty on air pollution and one is unlikely to emerge in the near future. The law on transboundary air pollution represents a patchwork of regional instruments, many of them having a soft-law nature. Overall, the legal landscape on transboundary air pollution can be described as *ad hoc* and fragmented with gaps in both geographical and substantive coverage (for example, regulated pollutants or pollution sources) (Yamineva and Romppanen 2017).

Alternative and innovative arrangements are currently being explored. Such arrangements are likely to take non-legally binding forms which have both advantages and limitations compared to international treaties. For example, in 2016 the Resolution on Air Quality at the UN Environment Assembly encouraged intergovernmental action to improve air quality (UNEP 2015). Further, the Resolution on Air Quality and Health at the World Health Assembly in 2015 recognized air pollution as the world's greatest environmental risk and highlighted the key role of health ministries. However, health ministries do not have the mandate to initiate the necessary changes to a country's energy landscape. Later in the same year, as highlighted throughout the report, air quality was formally recognized as a development concern with the inclusion of key indicators on air quality in SDGs 3, 11 and 13. The SDGs aim to address air pollution because it is a leading cause of death and disease worldwide, particularly for people residing in cities (WHO 2015).

In a best-case scenario, transnational institutions and organizations can encourage pro-environmental agencies within governments to enact policies; businesses to develop new corporate standards; and public values to place a greater premium on clear air. City networks such as Clean Air Asia may be particularly well positioned in this regard. These networks have become adept at providing new tools and transferring knowledge between countries, in part because they are more flexible than formal government-to-government agreements. Transnational networks of scientists – sometimes termed epistemic communities – also hold promise to strengthen the interface between science and policy.

3.6 CONCLUSIONS

This chapter reviewed trends in and concrete examples of the top 25 clean air measures in practice. Similar to Chapter 2, it divided those measures into three groups: conventional controls, next-stage measures and development priority measures. It demonstrated that achieving significant gains from reduced exposure to air pollution by 2030 is possible. By widely implementing the measures – of which there is already some knowledge and that have already demonstrated some success – a significant proportion of the people of Asia and the Pacific could live longer, healthier lives.

The chapter also draws several important conclusions for policy makers and other stakeholders as they contemplate how to implement those of the measures that fall in line with their priorities.

The Asia and Pacific region will not be able to grow its way out of air pollution problems. Continued economic growth will be critical to lifting millions of people out of poverty, but the successful adoption and effective implementation of pollution control measures will not result from growth alone. Rather, it is imperative that governments, businesses and civil society take action. For many countries, action will need to continue to strengthen implementation of the conventional controls while bringing the next-stage measures and development priority measures into air quality management programmes. This will require deliberate, solution-oriented, and evidence-based thinking among decision makers throughout the region.

There is no single set of solutions to air pollution. Different countries have selected different options to address similar problems. For instance, China and Japan are taking very different approaches to reducing emissions of VOCs from solvents. There are several factors that may influence the options that countries implement, ranging from the levels and rates of economic development and the sources and severity of pollution, to the magnitude and distribution of implementation costs and the dispersion or concentration of industrial structures. One of the main factors highlighted in this chapter is the differences in governance arrangements found throughout the region.

While the selection of solutions may vary, some patterns do emerge that may be instructive for countries at different levels of development. These include a pattern wherein national environmental agencies often work with other line agencies to introduce air quality standards and related legislation as part of initial efforts to implement conventional controls. From the early stages of development, it will be important that environmental agencies are able to have access to recent science on air pollution causes and impacts.

The timely provision of and easy access to this knowledge may enable leapfrogging in the introduction of air quality standards. Yet the necessary tightening of standards at early stages of development will be insufficient to achieve the required level of pollution control. Changing policy without adjusting allocations of human resources and supporting infrastructure would be likely to lead to significant implementation gaps in air quality standards. Commensurate increases in human resources and technical capacity are essential when standards tighten.

Many countries in the region have introduced additional sets of controls after adopting air quality standards. Frequently, these additional controls have drawn upon a broad range of instruments and compliance incentives that motivated polluting industries to adopt new technologies and/or change production processes. Compliance incentives can make the difference between an effective and ineffective policy.

In several cases, the growing awareness of the costs of air pollution (and the benefits of controls) led actors outside environmental agencies to come up with their own solutions to air pollution problems. These additional actors include cities that proposed innovative solutions to local problems. They also include politicians that use their position not only to introduce new policies but also to improve coordination across sectors and regions. Engaging cities early and involving them in decision making may help spur innovative solutions; creating political incentives may strengthen the political will to support institutional changes that can strengthen implementation and bring those innovative solutions to scale.

In moving beyond the conventional controls, enhanced coordination between environmental and agricultural agencies and across urban and rural areas will be critical. This will be particularly important in parts of Asia where there is significant but untapped potential to reduce emissions from manure and fertilizer. Working with agricultural agencies, large farms and agro-industry may be an important first step in realizing those potential gains. Similarly, cooperation between urban, peri-urban and rural areas will be needed to solve what appears to be chiefly urban air pollution.

In expanding the range of measures, stronger alliances should be sought with industries and interests promoting clean energy. The growth in renewables and energy efficiency has already had significant co-benefits for air quality improvement as well as climate change. Additional support from the air pollution community for well-designed feed-in tariffs, portfolio standards and energy auditing could enhance the attractiveness of these interventions, accelerate their uptake and expand their coverage.

Regional and international organizations can promote and help market many of the findings in this report. The CCAC, with its action-oriented approach, is well-positioned to advocate greater action in the Asia and Pacific region in line with the report's recommendations. The Asia Pacific Clean Air Partnership's (APCAP) emphasis on regional cooperation and atmospheric science can help ensure that decision makers in the region are basing their actions on the most recent science on sources, impacts and solutions. Development banks in the region can consider creating air pollution facilities that demonstrate proven solutions and leverage additional finance to scale their implementation.

ANNEXES

ANNEX 1

ANNEX 1.1 DESCRIPTION OF THE GLOBAL AMBIENT AND HOUSEHOLD AIR POLLUTION (AAP/HAP) MODELS

The integrated exposure-response (IER) approach assumes that:

1. exposure to $PM_{2.5}$ from diverse combustion sources is associated with increased mortality from ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD) and lung cancer (LC), and with increased incidence of acute lower respiratory infection (ALRI);

2. the toxicity of $PM_{2.5}$ differs only with regard to inhaled mass (exposure) and not with $PM_{2.5}$ composition;

3. the relation between $PM_{2.5}$ exposure and excess mortality rate ratios (RR) is not necessarily restricted to a linear function over the range of human exposure to $PM_{2.5}$ from diverse sources;

4. the relative risk of mortality from chronic disease experienced by people exposed to ambient air pollution (AAP), second-hand tobacco smoke (SHS), household air pollution (HAP), and active tobacco smoking (ATS) is a function of long-term cumulative exposure quantified in terms of daily average exposure concentration and does not depend on the temporal pattern of exposure. This assumption is required because the temporal nature of $PM_{2.5}$ exposure differs for AAP, SHS, HAP, and ATS; and

5. the relative risk associated with each type of exposure does not depend on the other types of exposure.

BOX A1.1.1: METHOD FOR SATELLITE AND CHEMICAL TRANSPORT MODEL-DERIVED ESTIMATES OF AMBIENT AIR POLLUTION USED IN GLOBAL BURDEN OF DISEASE CALCULATIONS

The approach undertaken by the Institute for Health Metrics and Evaluation (IHME) during the Global Burden of Disease (GBD) project for ambient air pollution exposure relies on air quality observations from satellites, combined with information from global chemical transport models and available ground measurements, to estimate global annual average exposure to $PM_{2.5}$ systematically, beginning in blocks, or grid cells, covering 0.1×0.1° of longitude and latitude (approximately 11x11 km at the equator).

This combination of data from ground-level monitoring with satellite observations and chemical transport models provides a globally consistent estimate of $PM_{2.5}$ concentrations. A detailed analysis of country-level trends in exposure was most recently conducted in 2016 using data in five-year intervals from 1990 to 2015. The GBD 2015 estimates for South Asia, for example, incorporate 44 measurements of $PM_{2.5}$ (and 419 of $PM_{2.5}$ estimates derived from PM_{10}) in India (25 directly measured $PM_{2.5}$/411 estimated from PM_{10}), Bangladesh (12/1), Bhutan (0/5), Nepal (0/1), Pakistan (7/0) and Sri Lanka (0/1). Taking into account the population in each grid cell within a country, the estimated exposure concentrations were aggregated to national-level population-weighted averages for a given year.

For ozone (O_3), a global chemical transport model was used to calculate a seasonal (summer) average for each grid cell, while accounting for variation in the timing of the O_3 season in different parts of the world. The process for estimating national-level population-weighted average O_3 exposures was the same (Cohen *et al*. 2017).

BOX A1.1.2: METHOD FOR MODEL-DERIVED ESTIMATES OF HOUSEHOLD AIR POLLUTION USED IN THE GLOBAL BURDEN OF DISEASE CALCULATIONS

Exposures to HAP have been defined in terms of annual average daily exposure to household concentrations of $PM_{2.5}$ resulting from the use of solid fuels, including agricultural residues, charcoal, coal, dung and wood. Data on fuel use are derived from a number of national and sub-national surveys, including demographic and health surveys, living standards measurement surveys, multiple indicator cluster surveys and country-specific sources, and from the WHO fuel-use database (GBD 2017b; World Bank 2016).

Since direct measures of HAP are reported only in a limited number of research studies (Balakrishnan *et al*. 2011; Northcross *et al*. 2015; Williams *et al*. 2015) estimation of exposure to HAP (for purposes of disease burden estimation) has been performed using spatiotemporal Gaussian process regression (GPR) modelling. Solid fuel estimates are first translated into indoor $PM_{2.5}$ concentrations and then into exposures separately for men, women and children. The first step – from fuel use estimates to room concentration estimates – relies on indoor $PM_{2.5}$ data from 90 studies in 16 countries. For GBD 2016, measured $PM_{2.5}$ concentrations were related to IHME's sociodemographic index and used to predict exposures for all locations and years (GBD 2017b; World Bank 2016). Indoor concentrations are translated to exposures by applying the ratio of personal exposures to area concentrations based on a sub-set of seven studies from six countries (GBD 2017b; World Bank 2016). The exact input measurements used for these estimates are unknown; as such, future work should validate estimated exposures with actual, repeated, on-the-ground measurements of exposure using personal aerosol samplers. Such work is underway as part of the PURE project (Arku *et al*. 2018).

While the assumptions do raise uncertainties regarding the burden estimates, without direct epidemiological evidence and without empirical evidence against which to evaluate those assumptions, the IERs have provided a consistent basis for estimating burdens attributable to AAP and HAP across world regions.

ANNEX 1.2 EXPERIMENTAL AND MODELLING STUDIES ON OZONE CROP IMPACTS

Studies carried out in open-top chambers (OTCs) under ambient ozone (O_3) concentrations revealed reductions in the yield of crops compared to those where ambient O_3 was filtered. Yield reductions in three wheat cultivars ranged between 8.6% and 20.7% (Rai *et al*. 2007; Rai *et al*. 2010) in India at mean ambient concentrations of 44 parts per billion (ppb), and in three cultivars between 37% and 46% in Pakistan at mean ambient O_3 concentrations of 60 ppb using OTCs (Wahid 2006). Similarly, reductions of 10.2–15.9% in four rice cultivars, 4.0–5.5% in two maize cultivars, 7.0–35.9% in four mustard cultivars and 12–20% in two soybean cultivars were reported at ambient O_3 concentrations, taking O_3 exposure of 50 ppb as the reference (Rai *et al*. 2016).

Yield reductions increased when crop plants were exposed to elevated levels of O_3 simulated in various experiments. Different cultivars of wheat showed yield reductions of 12.8–39.0% at ambient +10 ppb and 38–46% at ambient +20 ppb O_3 introduced for four hours daily from germination to maturity (Sarkar and Agrawal, 2010). Elevated O_3 levels in OTCs significantly reduced winter wheat yield compared with charcoal-filtered air (CF) control, i.e. by 8.5–58% for O_3 treatment one (AOT40 of 14.3–22.6 ppm.h) and 40–73% for O_3 treatment two (AOT40 of 24.2–61.9 ppm.h) treatments at the Jiaxing site, China (Wang *et al*. 2012). Similarly, Zhu *et al*. (2011) conducted a three consecutive seasonal free air concentration enrichment (FACE) study and reported that a mean 25% enhancement above ambient O_3 (45.7 ppb) reduced the wheat grain yield by 20% with a variation range of 10–35% among cultivars and seasons. The reduction of individual grain mass accounted mostly for the yield loss by O_3 that showed significant difference between the cultivars (Zhu *et al*. 2011). Akhtar *et al*. (2010) reported reductions varying between 11.6–47.6% at 60 ppb and 44.5–65.6% at 100 ppb O_3 exposure of two Bangladeshi wheat cultivars.

Rice cultivars showed yield reductions ranging from 27–31% at ambient +10 and from 30–45% at ambient +20 ppb O_3 (Sarkar and Agrawal 2012). As compared with the sub-ambient O_3 control, the mean yield losses in rice were 10–34% and 16–43%, respectively, when plants were exposed to O_3 treatment one (AOT40 of 13.8–29.5 ppm.h) and O_3 treatment two (AOT40 of 32.1–82.6 ppm.h) treatments, respectively, at the Jiaxing site, China (Wang *et al*. 2012). Similarly, elevated O_3 in the FACE experiments significantly reduced the grain yield by 12% when averaged across all the tested cultivars – hybrid rice cultivars SY63 and LYPJ, and inbred cultivars WJ15 and YD6 (Shi *et al*. 2009). An OTC study for two Malaysian local rice cultivars found that under the 8-h mean exposure of ozone of 32.5 ppb, the yield of one cultivar was reduced by 6.3% while the effect on the other cultivar was not statistically significant (Ishii *et al*. 2004). An OTC study conducted in peri-urban Hanoi, Viet Nam, found the grain yield loss of a locally grown Vietnamese rice cultivar to be 4.5% for every 10 ppb increase in O_3 from the ambient level of 6 ppb to the highest exposure level of 113 ppb, seven hours a day, 35 days covering the second half of the vegetative and early reproductive stages (Van *et al*. 2009).

Maize cultivars were found to be relatively resistant to elevated O_3 as yield loss varied from 7.2–9.5% and 10.1–13.8% respectively at ambient +15 and ambient +30 ppb O_3 concentrations (Singh *et al*. 2014). Among leguminous plants, mung bean showed reductions varying from 9.8–15.4% and soybean from 12–20% at ambient + 10 ppb elevated O_3 concentrations (Chaudhary and Agrawal, 2015; Singh *et al*. 2010). Oil-yielding crop mustard showed yield reductions of 12.5–48.5% among three cultivars (Singh *et al*. 2012) and one cultivar of sunflower showed 45.7% reduction at ambient +10 ppb O_3 concentration (Tripathi and Agrawal 2012). OTC experiments conducted for a local peanut cultivar in Viet Nam found significant reductions in plant height, leaf area and dry weight at harvest time due to exposure to elevated O_3. On average, the seed yield reduced by about 4.6% for every 10 ppb increase in O_3 from the ambient level of 6 ppb to a highest exposure level of 113 ppb, seven hours a day during 30 days of the flowering stage (Van and Kim Oanh 2009). The individual grain size was significantly decreased in wheat and rice exposed to elevated O_3 (Zhu *et al*. 2011; Shi *et al*. 2009). A summary of the results from experimental studies is given in Table A1.4.1.

Modelling methods for quantifying the impacts of ozone on crops

Two particular modelling methods are discussed below that can incorporate the direct and indirect impacts of O_3 on plant growth and ecosystem processes which are useful to assess yield loss in future climate conditions.

1) Semi-empirical O_3-effect modelling methods have been developed more recently; these use the same statistical relationships but are built in to process-based ecosystem modelling frameworks. It allows these models to assess the direct and indirect impacts of O_3 on plant growth and ecosystem processes such as photosynthesis, carbon (C) allocation and transpiration (Tai *et al*. 2014; Ren *et al*. 2007; Felzer *et al*. 2004; Ollinger *et al*. 1997; Reich 1987). Most land-ecosystem models are process based to simulate the dynamics in ecosystem function and structure as influenced by global environmental changes, from cell, leaf, community and ecosystem to regional and global levels, and from daily, monthly and seasonal to yearly and longer scales. Some of those models have incorporated O_3 effects, as one of multiple environmental drivers, on ecosystem C and water dynamics, using the statistical relationships described above, the most popular index being AOT40, used by Felzer *et al*. (2004), Ollinger *et al*.(1997) and Ren *et al*. (2007).

2) Dynamic process-based models that consider effective O_3 flux (the stomatal O_3 flux which exceeds the detoxification capacity of the plant) and effects on photosynthesis (Massman 2004; Martin *et al*. 2000); these approaches have been scaled to estimate consequent effects on C assimilation in forest canopies (Deckmyn *et al*. 2008; Martin *et al*. 2001) and for ecosystem plant functional types in the MOSES-TRIFFID land surface model (Sitch *et al*. 2007). However, few process-based O_3 models have been applied at a large scale due to limited O_3 flux data and complicated model parameterization and little attention has currently been devoted to developing such models for crops. An obvious way to achieve this is to develop a more comprehensive mechanistic approach to modelling O_3 impacts on crops.

TABLE A1.1.1 EFFECTS OF OZONE ON MAJOR CROPS AND FOREST TREES IN ASIA FROM THE EXPERIMENTAL STUDIES (% YIELD REDUCTION)

Species	**India/South Asia**	**China/East Asia**	**Southeast Asia**
Wheat	• OTC, 44 ppb (8h), 8.6–21% (Rai *et al*. 2007) • OTC, 60 ppb (8h), 37–46% (Wahid 2006) • OTC, +10 & +20 ppb (4h), 12.8 – 46% (Sarkar and Agrawal 2010) • OTC, 60–100 ppb (8h), 11.6–65.6% (Akhtar *et al*. 2010)	• FACE, +45.7 ppb (8h), 20% (Zhu *et al*. 2011) • OTC, 70–100 ppb, 8.5–58%; 150-200 ppb, 40–73% (Wang *et al*. 2012)	
Rice	• OTC, 35 ppb (8h), 34-38% (Wahid *et al*. 1995) • OTC, +10 & +20 ppb (12h), 27–45% (Sarkar and Agrawal 2012)	• OTC, +50–+100 ppb (8h), 8.2–26.1% (Feng *et al*. 2003) • FACE, +56–+59 ppb (8h), 15–17.5% (Shi *et al*. 2009) • OTC, 70–100 ppb, 10–34%; 150–200 ppb, 16-43% (Wang *et al*. 2012) • OTC, 60–100 ppb (8h), 3–34% (Inada *et al*. 2008; Yamaguchi *et al*. 2008)	• OTC, 32–113 ppb (7h), 10–48% (Van *et al*. 2009) • OTC, 32.5 ppb (8h), 6.3% (Ishii *et al*. 2004) • CC, 150 ppb (8h), 12.3% (Ariyaphanphitak *et al*. 2005)
Maize	OTC, +15 & +30 ppb (8h), 7.2–13.8% (Singh *et al*. 2014)		
Soya bean	• OTC, +10 ppb (4h), 12–20% (Singh *et al*. 2010) • EDU (400 ppm), 40–75 ppb (6h), 35–68% (Wahid *et al*. 2001)		

TABLE A1.4.1 EFFECTS OF OZONE ON MAJOR CROPS AND FOREST TREES IN ASIA FROM THE EXPERIMENTAL STUDIES (% YIELD REDUCTION) (contd.)

Species	India/South Asia	China/East Asia	Southeast Asia
Peanut			OTC, 32-113 ppb (7h), 27–49% (Van and Kim Oanh, 2009)
Mungbean	• OTC, +10 ppb (6h), 9.8–15.4% (Chaudhary and Agrawal, 2015) • EDU (500 ppm), 33 ppb (8h), 70% (Agrawal *et al*. 2005)		
Forest trees		• 8–15 ppm.h AOT for 6 months, 10% reduction of whole plant dry mass (Kohno *et al*. 2005) • OTC, 38.2 ppm.h (AOT40), 13–26% total biomass (Zhang *et al*. 2012)	
Other crops	OTC, +10 ppb (8h), 45.7 ppb for sun flower (Tripathi and Agrawal 2012)		

ANNEX 2

ANNEX 2.1 THE MODELLING TOOLS

In order to identify promising policy intervention options that could deliver effective improvements in air quality in Asia together with progress towards the Sustainable Development Goals, this report employs a suite of well-established scientific tools that deliver a holistic perspective that integrates geo-physical, economic, social and institutional dimensions across different spatial and temporal scales.

2.1.1 The Greenhouse gas – Air pollution Interactions and Synergies (GAINS) model

2.1.1.1 Overall approach

The GAINS model is a widely-applied policy analysis tool to identify cost-effective policy interventions to reduce the health impacts of air pollution while maximizing co-benefits with other policy priorities (Reis *et al*. 2012; Amann *et al*. 2011; Hordijk and Amann 2007).

As a scientific tool for integrated policy assessment, the GAINS model describes the air pollution pathways from atmospheric driving forces to environmental impacts. It brings together information on economic, energy and agricultural development, emission control measures and costs, atmospheric dispersion and source sensitivities. GAINS quantifies the emissions and impacts of nine air pollutants – sulphur dioxide (SO_2,) nitrogen oxides (NO_x), particulate matter with aerodynamic diameters equal to or less than 2.5 and 10 micrometres (μm) ($PM_{2.5}$ and PM_{10}), black carbon (BC,) organic carbon (OC), carbon monoxide (CO), ammonia (NH_3) and volatile organic compounds (VOCs) – and six greenhouse gases – carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs),

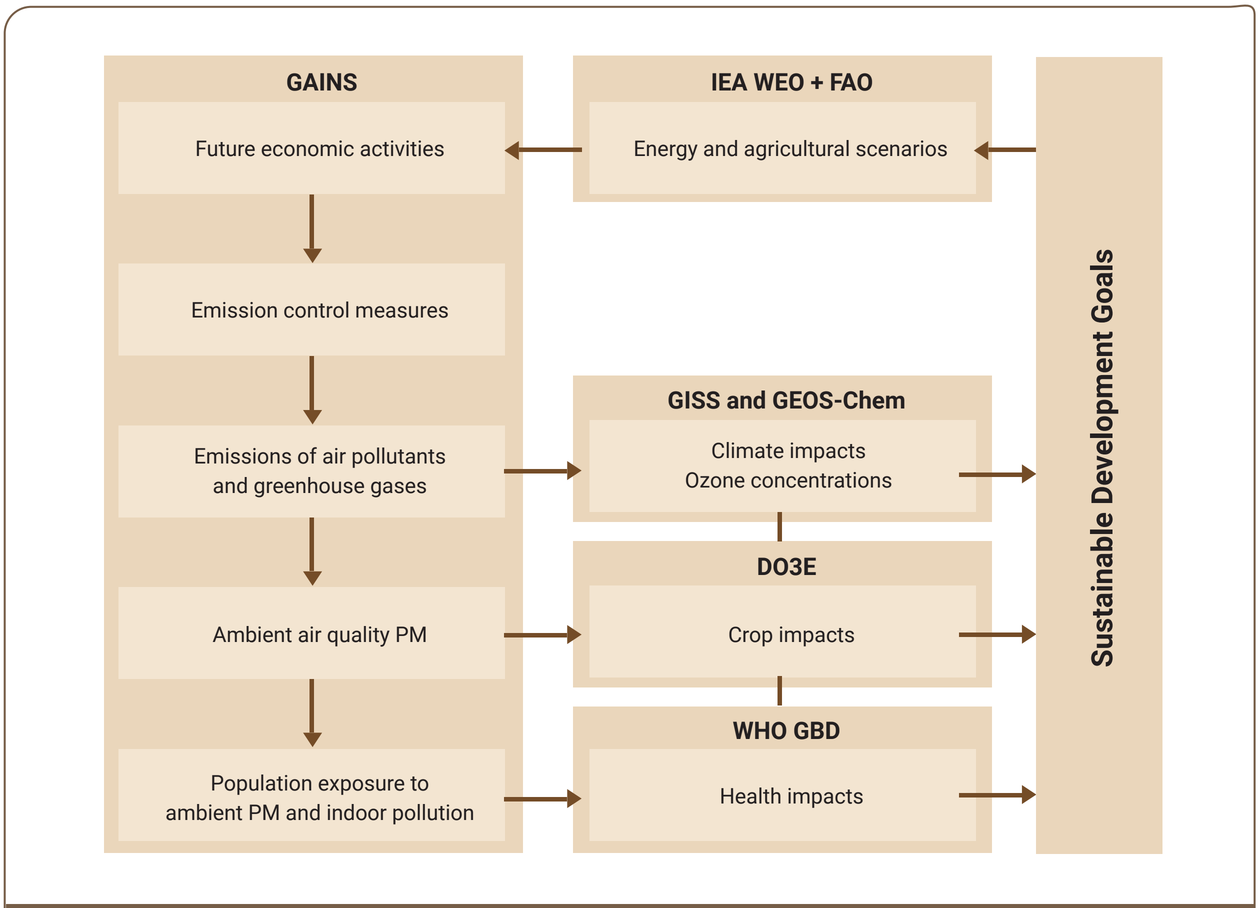


FIGURE A2.1: THE MODEL SUITE USED FOR THIS ANALYSIS AND THE INTERACTIONS BETWEEN MODELS perfluorocarbons (PFCs), sulphur hexafluoride (SF_6) – on human health, crops, acid deposition and long-term radiative forcing in a multi-pollutant/multi-effect perspective.

GAINS explores the co-control of more than 1,500 specific measures on multiple air pollutant and greenhouse gas emissions, identifies trade-offs and win-win measures, and assesses their impacts on ambient air quality, population exposure, resulting health and vegetation impacts, and various climate metrics.

GAINS is currently implemented for 196 countries/world regions with a global coverage, including more than 100 regions in Asia. The GAINS model and databases are accessible at http://gains.iiasa.ac.at.

The methodology follows the Global Burden of Disease (GBD) 2010/2013 studies and includes the effects of indoor pollution from household solid fuel use.

2.1.1.2 A multi-pollutant/multi-effect perspective

GAINS can follow pollutants from their sources to their impacts, and thereby simulates the impacts of specific policy interventions on multiple outcomes. In its optimization mode, GAINS identifies the least-cost balance of emission control measures across pollutants, economic sectors and countries that meet user-specified air quality and climate targets (Figure A2.2).

GAINS addresses air pollution impacts on human health from $PM_{2.5}$ and ground-level ozone (O_3), vegetation damage caused by ground-level O_3, the acidification of terrestrial and aquatic ecosystems and excess nitrogen (N) deposition of soils, in addition to the mitigation of greenhouse gas emissions. It captures the interactions between these multiple effects and the associated pollutants – SO_2, NO_x, particulate matter (PM), non-methane volatile organic compounds (NMVOCs), NH_3, CO_2, CH_4, N_2O, fluorinated gases (F-gases) – as well as the simultaneous co-control of multiple pollutants of specific emission reduction options (Figure A2.3).

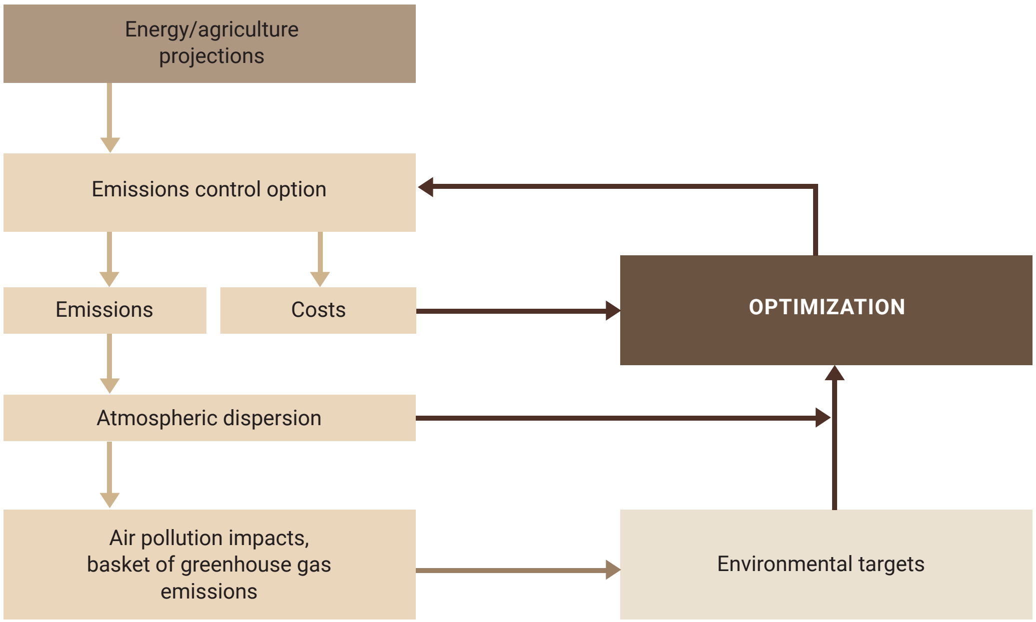


FIGURE A2.2: THE FLOW OF INFORMATION IN THE COST-EFFECTIVENESS ANALYSIS OF THE GAINS MODEL

2.1.2 Emission estimates

For each of the pollutants listed in Figure A2.3, GAINS estimates current and future emissions based on activity data, uncontrolled emission factors, the removal efficiency of emission control measures and the extent to which such measures are applied:

$$E_{i,p} = \sum_k \sum_m A_{i,k}\, ef_{i,k,m,p}\, x_{i,k,m,p}$$

where:

i, k, m, p	country, activity type, abatement measure, pollutant, respectively;
$E_{i,p}$	emissions of pollutant p (for SO_2, NO_x, VOCs, NH_3, $PM_{2.5}$, PM_{10}, BC, OC, CO_2, CH_4, N_2O, F-gases) in country l;
$A_{i,k}$	activity level of type k (e.g., coal consumption in power plants) in country i:
$ef_{i,k,m,p}$	emission factor of pollutant p for activity k in country i after application of control measure m;
$x_{i,k,m,p}$	share of total activity of type k in country i to which a control measure m for pollutant p is applied.

This approach allows capturing critical differences across economic sectors and countries that could justify differentiated emission reduction requirements in a cost-effective strategy. Structural differences in emission sources are reflected through country-specific activity levels. Major differences in emission characteristics of specific sources and fuels are represented through source-specific emission factors, which account for the degrees at which emission control measures are applied. GAINS estimates future emissions according to the equation above by varying the activity levels along exogenous projections of anthropogenic driving forces and by adjusting the implementation rates of emission control measures.

	PM (BC, OC)	SO_2	NO_x	VOC	NH_3	CO	CO_2	CH_4	N_2O	HFCs PFCs SF_6
Health impacts:										
PM (Loss in life expectancy)	●	●	●	●	●					
O_3 (Premature mortality)			●	●		●		●		
Vegetation damage:										
O_3 (AOT40/fluxes)			●	●		●		●		
Acidification (Excess of critical loads)		●	●		●					
Eutrophication (Excess of critical loads)			●		●					
Climate impacts:										
Long-term (GWP100)	○	○	○	○	○	○	●	●	●	●
Near-term forcing	●	●	●	●	●	●	○	●	○	○
Carbon deposition to the Arctic and glaciers	●									

Note: ● – important impact; ○ – small impact. GWP – global warming potential.
AOT40 – the sum of the differences between hourly O_3 concentration and 40 parts per billion (ppb) for each hour when the concentration exceeds 40 ppb during a relevant growing season.

FIGURE A2.3: THE MULTI-POLLUTANT/MULTI-EFFECT FRAMEWORK OF THE GAINS MODEL

2.1.3 Air pollution control costs

Basically, three groups of measures to reduce emissions can be distinguished:

- Behavioural changes reduce anthropogenic driving forces that generate pollution. Such changes in human activities can be autonomous (for example, changes in life styles), they could be fostered by command-and-control approaches (for example, legal traffic restrictions), or they can be triggered by economic incentives (for example, pollution taxes, emission trading systems, etc.). The GAINS concept does not internalize such behavioural responses, but reflects such changes through alternative exogenous scenarios of the driving forces.

- Structural measures that supply the same level of (energy) services to the consumer but with less polluting activities. This group includes fuel substitution (for example, switching from coal to natural gas) and energy conservation/energy efficiency improvements. The GAIN model introduces such structural changes as explicit emission control options.

- A wide range of technical measures has been developed to capture emissions at their sources before they enter the atmosphere. Emission reductions achieved through these options neither modify the driving forces of emissions nor change the structural composition of energy systems or agricultural activities. GAINS considers about 1,500 pollutant-specific end-of-pipe measures for reducing SO_2, NO_x, VOCs, NH_3 and PM emissions and several hundred options for greenhouse gases and assesses their application potentials and costs.

The GAINS model estimates the various costs of the dedicated emission control measures. These estimates are based on international experience in technology costs and consider country-specific circumstances that justify differences in costs across countries for objective reasons. GAINS does not, however, quantify the full costs of system changes (for example, of a decarbonization strategy) that imply important (macro-economic) feedbacks and potential changes in international competitiveness. Also, the GAINS model does not quantify costs of behavioural changes, as it does not assess welfare costs and consumer utilities.

Assuming a free market for emission control technologies, the same technology will be available to all countries at the same costs. However, country- and sector-specific circumstances (such as size distributions of plants, plant utilization, fuel quality, energy and labour costs, etc.) lead to justifiable differences in the actual costs at which a given technology removes pollution at different sources. For each of the 1,500 emission control options, GAINS estimates their costs of local application considering annualized investments (I_{an}), fixed (OM_{fix}) and variable (OM_{var}) operating costs, and how they depend on technology m, country i and activity type k. Unit costs of abatement (*ca*), related to one unit of activity (*A*), add up to:

$$ca_{i,k,m} = \frac{I^{an}_{i,k,m} + OM^{fix}_{i,k,m}}{A_{i,k}} + OM^{var}_{i,k,m}$$

Thus, cost figures estimated with GAINS refer to the costs of implementing dedicated emission control measures. They do not include benefits from lower emissions that lead to cleaner air, such as improved health conditions, crop productivity and undisturbed ecosystems.

GAINS estimates costs of societal resources diverted for the purposes of emission reductions. These estimates do not include transfer payments (for example, taxes, profits, subsidies), as these do not represent net costs to the society. Up-front investments are annualized over the technical lifetime of the equipment, using a discount rate of 4% that is appropriate for social planning purposes. Obviously, private actors that need to consider profits, taxes and other cost components will apply different discount rates.

2.1.4 Modelling methane emissions

The estimation of anthropogenic CH_4 emissions in the GAINS model follows the same general bottom-up emission inventory approach as used for other pollutants in GAINS; activity levels multiplied by emission factors that have been adjusted for impacts on emissions from adopted control technology. A future emissions possibility range is identified between a baseline emission scenario that describes future emissions without further uptake of emission control technology than prescribed in current legislation, and a maximum technically feasible reduction (MFR) scenario that describes the lowest possible emissions given that existing control technology is implemented to a maximum feasible extent. The emission reduction pathway between the baseline and MFR scenarios is described by a marginal abatement cost curve. The GAINS model covers all anthropogenic sources of CH_4 emissions, that is emissions from livestock enteric fermentation and manure management, anaerobic decomposition of organic waste and wastewater, incomplete combustion, and fugitive emissions from fossil fuel extraction, processing, transmission and distribution (Höglund-Isaksson 2012).

Livestock CH_4 emissions are estimated from the Food and Agriculture Organization of the United Nations (FAO) activity levels and country-specific emission factors that take account of different types of manure management systems, milk productivity levels and indoor housing times. Identified abatement potentials include breeding schemes targeted at improving both productivity and animal fertility and longevity, options to change animal feed composition and anaerobic digestion of manure for biogas recovery.

The GAINS model includes an extensive structure for estimating emissions from flows of different types of solid waste – food, paper, textile, wood, plastics/rubber, etc. – from both industrial and municipal sources. Activity data on generation of different types of waste in historical years is taken from international statistics databases and projected into the future by taking account of impacts from changes in per person income levels and urbanization rates. The future abatement potential is determined by identifying possible improvements to the current destination of solid waste flows, that is, to what extent solid waste is centrally collected or not, and if collected, to what extent it is recycled, incinerated with or without energy recovery, or disposed of at managed or unmanaged landfills, and if uncollected, to what extent it is openly burned or simply scattered.

Fugitive CH_4 emissions from coal mining, oil and gas extraction, and natural gas transmission and distribution are estimated making extensive use of country/region- specific information on, for example, calorific values of coal, oil and gas, surface or underground coal mining, generation and recovery rates of associated petroleum gas, volumes of associated gas flared as estimated from satellite images, offshore or onshore production, extent of unconventional gas production and length of onshore gas transmission pipelines. Abatement potentials in coal mining are assessed separately for emissions released during degasification activities before mining begins, during mining through ventilation shafts or during post-mining activities. For oil and gas extraction, abatement potentials are assessed separately for the handling of associated gas and for unintended leakages from equipment and processes. Finally, leakage from consumer gas distribution networks is accounted separately for domestic and industrial/power plant users to reflect different average leakage rates (Höglund-Isaksson 2012).

2.1.5 Modelling hydrofluorocarbon emissions

A baseline projection of future HFC emissions in Asia has been developed following the methodology described by Purohit and Höglund-Isaksson (2017). For major sources – residential and commercial air conditioning, mobile air conditioning and domestic refrigeration – the consumption of HFC in historical years 2005 and 2010 has been derived in a consistent manner across countries, starting from a compilation of data on underlying drivers, such as number of vehicles by vehicle types, commercial floor space area, cooling degree days, per person income, average household sizes, current equipment penetration rates, etc. Hydrofluorocarbon consumption in commercial and industrial refrigeration, refrigerated transport, foams and other smaller HFC sources, varies greatly between countries, due for example to differences in industrial structures and consumption patterns, which makes it more challenging to model the HFC consumption consistently across countries from underlying data. For these sectors, information on HFC consumption has been compiled from various published sources (GIZ 2014; UNDP 2014a, b; UNEP 2011; MoEF 2009), or has been derived in a consistent manner from underlying activity data using default factors from literature.

Drivers for future HFC consumption are consistent with the macroeconomic development projected in the 2016 World Energy Outlook (WEO) of the International Energy Agency (IEA) (IEA 2016). Effects on HFC emissions from uptake of alternative technologies and/or substances are only accounted for to the extent that these technologies have already been adopted or will be required to be adopted in the future to comply with implemented legislation, for example, Japan's Act on the rational use and proper management of fluorocarbons. The baseline does not account for future uptake of abatement technology on the sole basis of estimated marginal abatement costs turning out zero or negative. Apart from uncertainty being high in cost estimates in general, there may exist other barriers for technology spread and adoption, such as institutional or informational barriers, which are difficult to reflect in a general model setting like GAINS.

2.1.6 Modelling ambient levels of $PM_{2.5}$

Ambient air quality in each scenario is estimated with the GAINS model. The annual ambient $PM_{2.5}$ concentration in GAINS includes two components:

1) a regional background concentration related to emissions from remote and high-stack sources, calculated with linear source-receptor transfer coefficients from sensitivity simulations of the European Monitoring and Evaluation Programme (EMEP) chemical transport model (Simpson *et al*. 2012) at a resolution of 0.5×0.5°;

2) a sub-grid increment related to primary $PM_{2.5}$ (PPM) emissions from local low-level sources, including domestic and transport emissions as well as open burning of waste. The combined results are used to estimate population exposure to ambient $PM_{2.5}$ concentrations.

The response of ambient $PM_{2.5}$ concentrations to emission changes of PPM, SO_2, NO_x, NH_3, and VOCs in each region (section 2.1.2) is computed with transfer coefficients, which have been derived from sensitivity simulations with a full EMEP atmospheric chemistry transport model on a 0.5×0.5° grid (Simpson *et al*. 2012). In each sensitivity simulation, emissions of one pollutant (PPM, SO_2, NO_x, NH_3, VOCs) from one source region are reduced by 15%. For PPM, additional sensitivity simulations were undertaken which reduce only low-level sources. Linearizing the response of grid concentrations to these emission changes yields the transfer coefficient, i.e. the impact of one unit of emissions of pollutant emitted from region on ambient concentrations in grid cell :

$$\pi_{pji} = \frac{\Delta\left[\mathrm{PM}_{2.5}\right]_{\mathrm{i}}}{\Delta E_{pj}}$$

Total $PM_{2.5}$ concentrations in each grid cell are then calculated as the sum of transfer coefficients multiplied with the scenario emissions:

$$\left[\mathrm{PM}_{2.5}\right]_{\mathrm{i}} = \delta_{\mathrm{i}} + \sum_{p} \sum_{j} \pi_{pji} \cdot E_{pj}$$

where δ_i is a grid-specific residual from boundary conditions and nonlinearities, which is a small positive value for most grid cells.

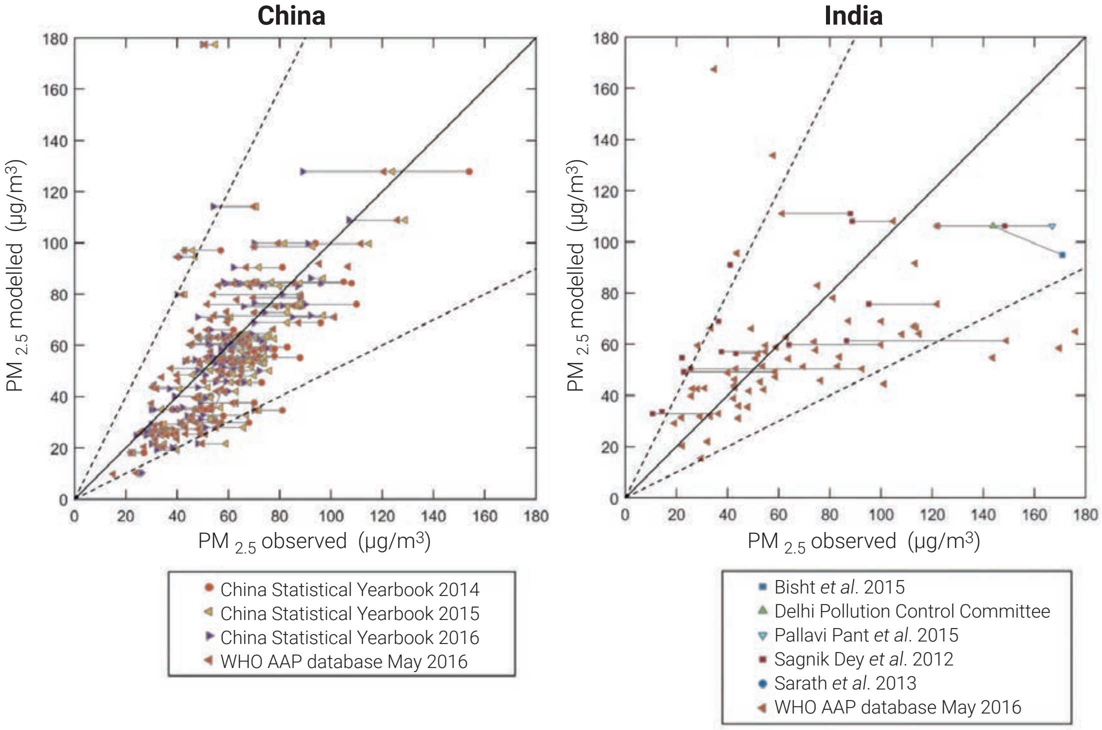
For cities of more than 100,000 inhabitants, concentrations are calculated individually below the grid resolution. GAINS employs the assumption that fine-scale variations in ambient PM concentrations are mainly related to emissions of primary PM from low-level sources such as residential combustion, road traffic, and open burning of waste (Kiesewetter *et al*. 2015). Therefore, modelled concentrations are re-distributed within each grid cell, reflecting the spatial pattern of low-level emission sources which is derived by combining fine resolved population data at approximately 100x100 metres (m) resolution obtained from worldpop.org.uk (Gaughan *et al*. 2013), with information on urban and rural preferences of household fuel use. The local transfer coefficient applied to low-level emissions is derived from a linear regression on the additional perturbation run changing only the low-level emissions.

Validation of model results for ambient $PM_{2.5}$

Figures A2.4 and A2.5 show scatter plots of modelled annual mean $PM_{2.5}$ concentrations for individual cities in 2015, compared to observations. The availability of monitoring data differs strongly between individual countries – while in China a large data set is publicly available through the statistical yearbooks, the data coverage in many other countries is rather low and the quality of monitoring data is uncertain. In many cases the World Health Organization (WHO) Ambient Air Quality database is the only publicly available source of information. However, reported $PM_{2.5}$ values are often not directly measured but derived from PM_{10}, as direct $PM_{2.5}$ measurements are not always available. The degree of agreement between model and observations varies between individual countries – notably, there is good agreement and high correlation in China, a country with a particularly large and rather reliable data set of $PM_{2.5}$ ground-level measurements.

Comparison with results from other models

While comparing model results against monitoring data is essential for establishing credibility, the current paucity of monitoring data for $PM_{2.5}$ in many Asian countries does not allow a full spatial coverage of such comparison. Thus, it is instructive to compare concentration fields obtained with different atmospheric chemistry models. To this end, only a limited comparison has been carried out, restricted to results of GAINS and the NAQPMS model of the Institute of Atmospheric Physics of the Chinese Academy of Sciences (CAS) in Beijing. Both models have been run for the meteorology of 2015, with independent emission estimates for 2015. In general, there is a good match of computed $PM_{2.5}$ concentrations, although GAINS estimates higher values in the west of Asia, due to larger emissions of natural sources (soil dust) (Figures A2.6 and A2.7).



Note: Different observational data sets are indicated by different symbols. Observations referring to the same city are connected by lines to indicate the inter-annual and spatial variability within a city.

FIGURE A2.4: COMPARISON OF GAINS MODEL RESULTS WITH NATIONAL MONITORING DATA AND SATELLITE-BASED DATASETS (DEY *et al.* 2012, FOR INDIA), AS WELL AS DATA REPORTED IN THE WHO DATABASE (2016)

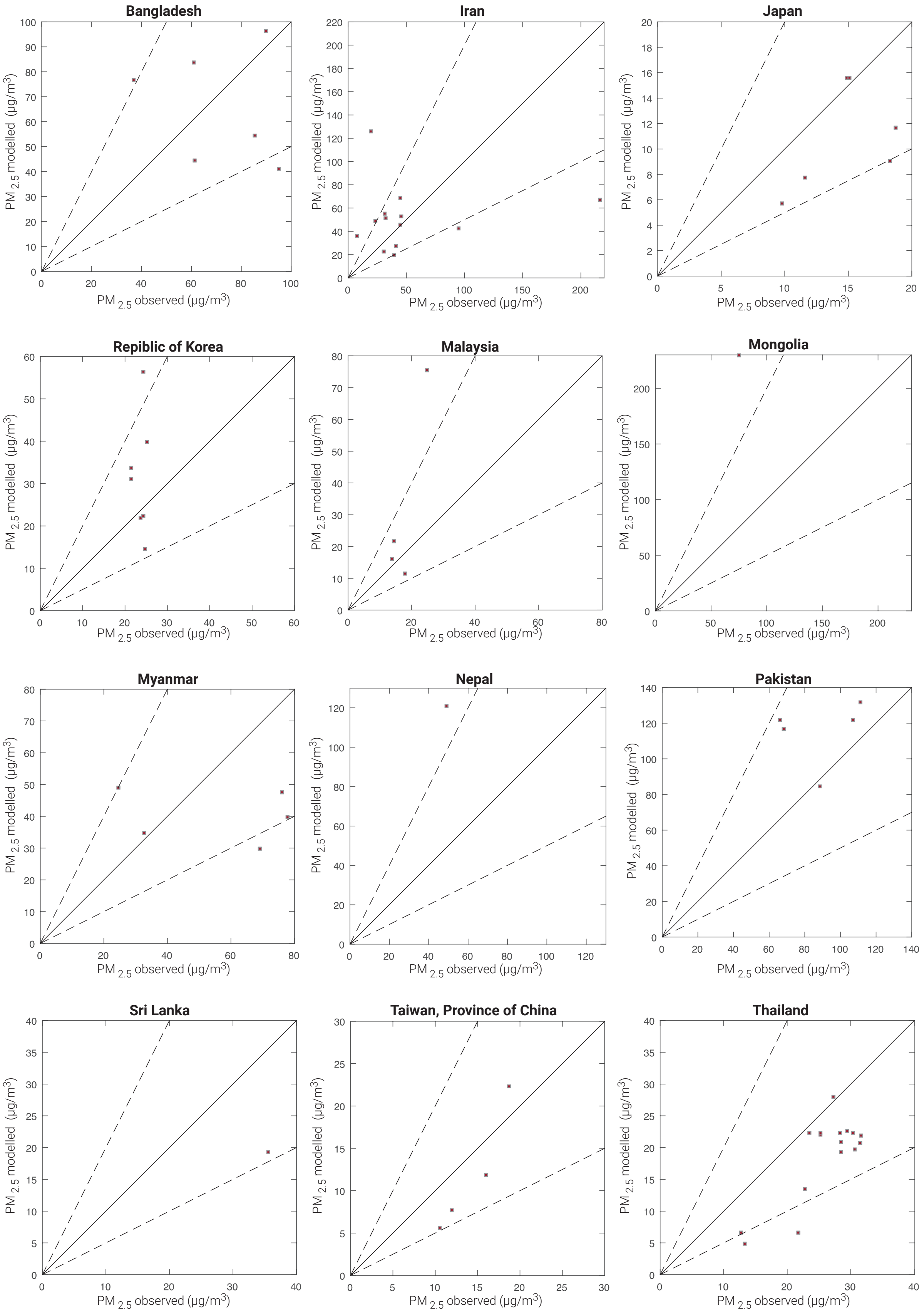


FIGURE A2.5: COMPARISON OF GAINS MODEL RESULTS WITH DATA REPORTED IN THE WHO DATABASE (2016)

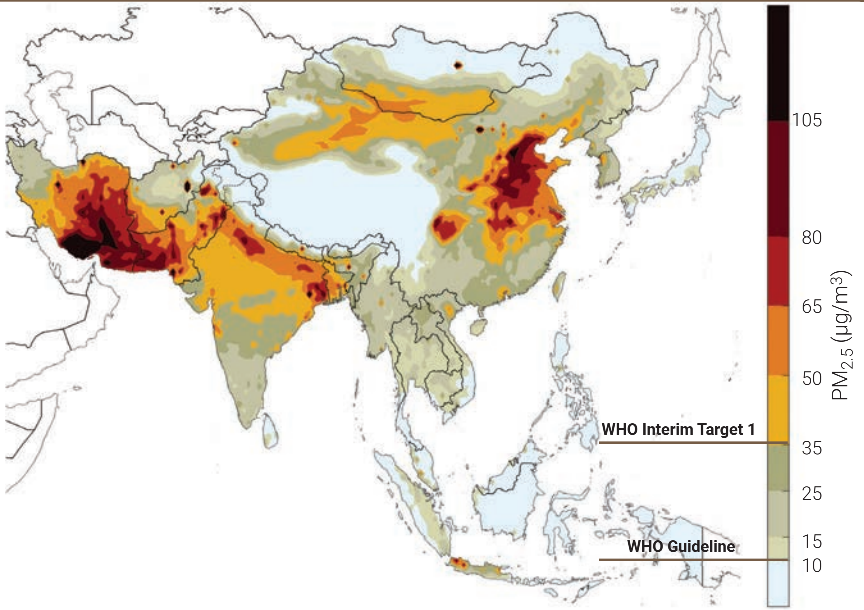


FIGURE A2.6: AMBIENT LEVELS OF PM$_{2.5}$ IN ASIA IN 2015 AS MODELLED BY GAINS

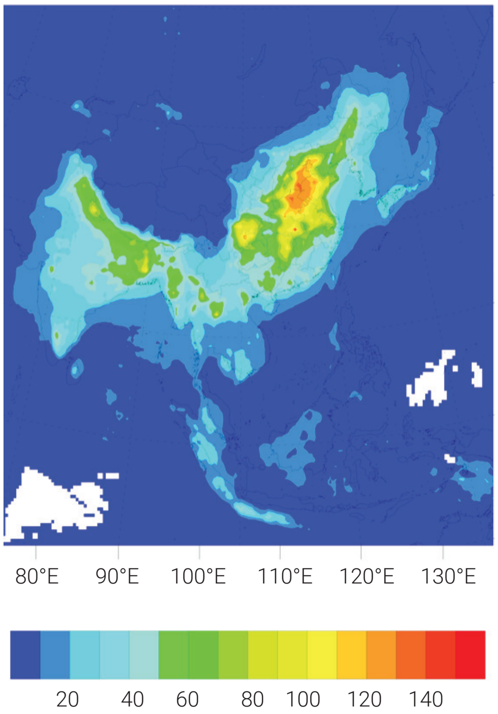


FIGURE A2.7: LEVELS OF PM$_{2.5}$ IN AMBIENT AIR IN 2015 (μg/m^3)

Source: CAS, Beijing, China

2.1.7 Population exposure to $PM_{2.5}$

As a metric for population exposure to $PM_{2.5}$ in ambient air, GAINS computes the annual average population-weighted mean concentrations of ambient $PM_{2.5}$. For this purpose, calculated $PM_{2.5}$ concentrations at the spatial resolution of urban and rural parts of each 0.5° grid cell are multiplied with population numbers specified at the same resolution for the same scenario year, summed across the region and then divided by the total population for the respective region. Fine-scale gridded population is based on open-source data sets at approximately 100×100m resolution developed by worldpop.org.uk (Gaughan *et al*. 2013). Total country population numbers are calibrated to UN world population statistics for 2010 and subject to national population trends from the UN World Population Prospects 2010 (UNDESA 2011), taking into account future urbanization trends as estimated in the UN World Urbanization Projections 2011 (UNDESA 2012).

2.1.8 Health impacts from ambient $PM_{2.5}$

GAINS computes the impact on the projected future population of exposure to ambient $PM_{2.5}$ after first calculating the impact of primary PM, SO_2, NO_x, NH_3, and VOC emissions in each of the 100 regions in Asia on ambient $PM_{2.5}$ concentrations, as described in section 2.1.6. To capture the level of concentration of $PM_{2.5}$ in cities, grid concentrations are calculated separately for the urban and rural parts of each grid cell. The resulting $PM_{2.5}$ levels are used to estimate population exposure.

The health impact assessment follows the methodology developed in the context of the GBD 2013 assessment (Forouzanfar *et al*. 2015) and applied by WHO (2016) in their Burden of Ambient Air Pollution assessment. Relative risk of mortality is calculated for all relevant diseases (ischemic heart disease, chronic obstructive pulmonary disease, stroke, lung cancer and acute lower respiratory infections) from the integrated exposure-response (IER) relationships used in the above-mentioned studies. Country-specific baseline mortality rates for five-year-interval age groups are derived from UN data (UNDESA 2011) for all scenario years.

The country- and age-specific relative contributions of individual diseases to total baseline deaths are taken from the GBD 2013 assessment (Forouzanfar *et al*. 2015) and, in the absence of better information, are assumed to remain constant in the future. The approach inherently takes into account the effect of the ageing population, which increases the number of people vulnerable to air-pollution-related diseases over time. For historic years, the resulting central estimates are well within the uncertainty ranges of other studies such as GBD 2013 (WHO 2016).

The calculation of total air pollution-related deaths assumes that ambient and indoor pollution are independent risks.

The uncertainties of health impact calculations are quantified employing a full Monte Carlo approach for the key parameters of the disease-specific IER functions including the counterfactual concentrations.

2.1.9 Health impacts from exposure to indoor pollution

The exposure of indoor air pollution is calculated for residents using solid fuel for cooking. A typical exposure of 300 micrograms per cublic metre ($\mu g/m^3$) is assumed for traditional stoves and 70 $\mu g/m^3$ for clean stoves, based on the wide range of observed concentrations (Balakrishnan *et al*. 2013). Corresponding relative risks are derived from the GBD 2013 IER functions which are used in this assessment (Forouzanfar *et al*. 2015). The numbers of solid fuel users using traditional and clean cookstoves have been estimated by the IEA, coherent with the different energy scenarios (IEA 2016).

The human health impact in terms of the premature mortalities of each scenario is estimated for all relevant diseases, including ischemic heart disease, stroke, chronic obstructive pulmonary disease, lung cancer and acute lower respiratory infections in five-year steps, equivalent to the calculations for ambient air pollution.

ANNEX 2.2 THE GISS COMPOSITIONCLIMATE AND GEOS-CHEM CHEMICAL TRANSPORT MODELS

2.2.1 Modelling ground-level ozone

Estimates of concentration levels of ground-level O_3 resulting from the emission scenarios produced by GAINS have been estimated with:

i) the Goddard Institute for Space Studies GISS) Global Climate Model; and
ii) the GEOS-Chem atmospheric chemistry transport model.

Ozone concentrations were simulated globally at 2x2.5° resolution in these models. Identical gridded anthropogenic emissions for the current legislation and climate policy scenarios at 0.5x0.5° resolution were used as input into both models.

ModelE2 simulates both the general circulation and chemistry of the atmosphere, with the internally generated meteorology fully interacting with the gaseous and aerosol chemistry. These interactions are fully discussed in Schmidt *et al.* (2014). A thorough evaluation of the O_3 chemistry and the processes contained within ModelE2 can be found in Shindell *et al.* (2013). In short, for processes applicable to this analysis, tropospheric NO_x-(HO_x)-O_x-CO-CH_4 chemistry, which also includes peroxyacyl nitrates (PAN), isoprene, alkyl nitrates, aldehydes, alkenes, and paraffins are simulated.

ModelE2 features online calculations of NO_x from lightning, online calculations of biogenic isoprene and terpenes, online calculations of natural dust (Miller *et al.* 2006), online calculations of sea-salt emissions (Koch et al. 2006), prescribed biogenic alkene and paraffin emissions, NO_x emissions from soil, and prescribed volcanic emissions (Miller *et al.* 2014).

All GEOS-Chem simulations were run using 2015 GEOS-FP assimilated meteorology, provided by the Global Modeling and Assimilation Office (GMAO) at the NASA Goddard Space Flight Center, and the secondary organic aerosol (SOA) chemical mechanism (Pye *et al.* 2010; Pye and Seinfeld 2010), which simulates the coupled oxidant-aerosol chemistry of the troposphere. In contrast to the ModelE2 simulations, due to the consistent driving meteorology in all simulations, the impacts of a changing climate were not captured and the differences between the time-sliced simulations are strictly due to emission changes. All simulations featured a 1-year spin-up period, followed by the full-year simulations that were used in the analysis. With the exception of volcanic SO_2 and biomass burning emissions, which were retrieved from the AEROCOM dataset and the Global Fire Emissions Database (GFED4) (Giglio *et al.* 2013), respectively, all non-anthropogenic emissions respond to meteorology within the model. This includes lightning NO_x (Murray *et al.* 2012), soil NO_x (Hudman *et al.* 2012), biogenic emissions (MEGAN; Guenther *et al.* 2006), and dust emissions generated from the dust entrainment and deposition (DEAD) scheme (Zender *et al.* 2003). All emissions were processed through the Harvard NASA Emission Component (HEMCO; Keller *et al.* 2014). Speciation of total VOC emissions was spatially and sectorally delineated globally using the REanalysis of TROpospheric chemical composition (RETRO) emissions inventory, consistent with the methods applied in Hoesly *et al.* (2017) for the Community Emission Data System (CEDS) and CMIP6. Surface O_3 concentrations from GEOS-Chem were calculated using the method outlined in Zhang *et al.* (2012).

Since ModelE2 simulates its own meteorology, three realizations of the current legislation and climate policy scenarios were simulated, each with separate initial conditions. Only one simulation using GEOS-Chem was used for each time slice (2015, 2030, and 2030 with climate policy). Additional details regarding both models, as well as an evaluation of applicable health and agriculture impact metrics, can be found in Seltzer *et al.* (2017).

2.2.2 Population exposure to ozone

Gridded estimates of O_3 concentrations output from GISS and GEOS-Chem, at 2x2.5º resolution for 2015 and 2030 current legislation and climate policy scenarios, were used to estimate population-weighted O_3 concentrations for the four sub-regions, and for Asia as a whole. The proportion of the population in each region within each grid square was estimated based on the population distribution in the Gridded Population of the World v3

TABLE A2.1 POPULATION-WEIGHTED O_3 CONCENTRATIONS ESTIMATED FROM THE GISS AND GEOS-CHEM MODELS

Region	2015 current legislation baseline population-weighted O_3 (ppb)		2030 current legislation baseline population-weighted O_3 (ppb)		2030 climate policy population-weighted O_3 (ppb)	
	GISS	GEOS-Chem	GISS	GEOS-Chem	GISS	GEOS-Chem
East Asia	86.5	66.2	74.0	59.1	56.2	51.3
High-income countries	77.7	53.8	73.1	48.5	57.7	43.5
South Asia	74.9	63.1	81.8	66.3	63.7	57.9
Southeast Asia	51.2	49.7	53.0	52.2	34.5	40.9
Asia	75.4	61.7	74.4	60.8	56.4	52.3

Note: O_3 exposure metric is the 6-month maximum daily maximum 1h O_3 concentration.

population distribution datasets (CIESIN 2005). From hourly O_3 concentrations output separately from the GISS and GEOS-Chem models at 2x2.5° resolution, the daily maximum one-hour (1h) concentrations were calculated. Six-month running mean average daily maximum 1h concentrations were then calculated, with the maximum of these values being taken as the value of the O_3 exposure metric in each grid. This metric was selected to characterize population-weighted O_3 exposure for consistency with the metric used in the Jerrett *et al*. (2009) epidemiological study that calculated the relative risk applied to estimate O_3 health burdens (section 2.2.3). Population-weighted O_3 concentrations for each region are shown in Table A2.1.

2.2.3 Health impacts from ground-level ozone

The health burden associated with O_3 exposure was calculated using the methodology described in Anenberg *et al*. (2010), and that has been applied extensively to estimate global ozone-associated premature deaths (Forouzanfar *et al*. 2016; Silva *et al*. 2016a, b; Forouzanfar *et al*. 2015; Lelieveld *et al*. 2015; Silva *et al*. 2013; Lim *et al*. 2012). Premature deaths associated with ozone exposure were calculated using Equation 1:

$$(1)\ \Delta \text{Mort} = y_0(1 - \text{exp-}^{\beta \Delta X})\text{Pop.}$$

$$(2)\ \text{RR} = \text{exp}^{\beta \Delta Y}$$

where ΔMort is the change in mortality associated with long-term O_3 exposure, y_0 is the baseline mortality rate for respiratory diseases, Pop. is the exposed population, ΔX is the O_3 exposure estimate, above a low-concentration cut-off, and β is the effect estimate (natural log of the relative risk (RR)) for the association between long-term O_3 concentrations and respiratory mortality (Equation 2).

Here, the RR (RR = 1.040; 95% CI: 1.013, 1.067) was derived from analysis of the association between long-term O_3 exposure and respiratory mortality in a cohort of US citizens (Jerrett *et al*. 2009). In Jerrett *et al*. (2009), it was calculated that for a 10 ppb increase in O_3 exposure, quantified as the April-September average of the daily maximum

1h O_3 concentration, resulted in a 4% increase in respiratory disease among the cohort population, who were all more than 30 years old.

The exposed populations in 2015 and 2030 were taken from UN Population Division statistics, and disaggregated in 5-year age groups from 25–29, 30–34, etc. up to 80+ years, in line with the age groupings used to estimate $PM_{2.5}$-associated premature mortality (UNDESA 2017). The population in each country was distributed according to the Gridded Population of the World v3 population distribution datasets (CIESIN 2005).

National, baseline respiratory mortality rates for 2015 were taken from the GBD 2016 study (Abajobir *et al*. 2017), as the combined disease rate from the chronic respiratory diseases, lower respiratory infections and upper respiratory infections GBD disease categories. To estimate future national respiratory disease mortality rates, the 2015 respiratory disease rates for each country was projected to 2030, based on the change in overall death rate in each country estimated in the UN Population Division statistics (UNDESA 2017). Hence it was assumed that the proportion of deaths from respiratory diseases remains the same in 2030 as in 2015.

The O_3 exposure metric for the population in each 2x2.5° grid was the 6-month maximum daily maximum 1h O_3 concentration, consistent with the exposure metric used in Jerrett *et al*. (2009). A low-concentration cut-off was applied – a cut-off below which no excess risk from O_3 exposure was assumed. This level was the minimum exposure level in the Jerrett *et al*. (2009) cohort study, and set at 33.3 ppb. Hence when the O_3 concentration in a grid was greater than 33.3 ppb, ΔX was the difference between the O_3 concentration in the grid, and 33.3 ppb. When the O_3 concentration was less than 33.3 ppb, ΔX was set at 0 ppb.

Equation 1 was applied to estimate premature deaths associated with O_3 exposure for each age group individually in 2015, and for the 2030 current legislation baseline and 25 clean air measures scenarios. Uncertainty ranges for premature deaths, accounting for uncertainty in the effect estimates, were generated by Monte Carlo simulations. For each run, 1,000 values of RR, and hence β, were generated based on the uncertainty range reported for the RR in Jerrett *et al*. (2009). This resulted in 1,000 estimates of premature deaths, from which 95% confidence intervals were derived. The mean and 95% confidence intervals of premature death estimates derived using the GISS and GEOS-Chem O_3 exposure estimated were then calculated.

2.2.4 Vegetation impacts from ground-level ozone

The O_3-induced crop loss for four staple crops, maize, rice, soy and wheat, was estimated based on a methodology used previously to estimate global crop-yield loss due to O_3 damage (Shindell *et al.* 2012; van Dingenen *et al*. 2009). The equations used to derive relative yield loss (RYL), and crop production loss (CPL), are shown in Equations 3 and 4, respectively.

$$(3)\ RYL = 1 - \exp[-MX/a^b]/\exp[-RC/a^b]$$

Where MX = O_3 exposure metric (M7 for rice and wheat, and M12 for maize and soy)
RC = reference concentration
a, b = crop-specific parameters

$$(4)\ CPL = \frac{RYL}{[1-RYL]}\ x\ CP$$

Where CPL = crop production loss
CP = crop production
RYL= relative yield loss

Crop production (year 2000 estimates), and representative growing season start months were available for 1x1° grids globally, as derived in van Dingenen *et al*. (2009) by distributing national crop production estimates across a country using the global agro-ecological zones (GAEZv3) suitability index dataset for each crop (http://gaez.fao.org/Main.html).

The O_3 exposure metrics were calculated as the average daytime O_3 concentration across a representative 3-month growing season for each crop. For rice and wheat, daytime was between 09:00 and 15:59 (termed the M7 metric), and for maize and soy it was between 08:00 and 19:59 (M12 metric). The difference reflects the different O_3 exposure metrics relevant for the concentration-response functions applied. The hourly O_3 concentrations output from the GISS model were used to calculate the M7/M12 metric value for each grid and each crop as the average daytime O_3 concentration across the growing season start month, and subsequent two months.

Relative yield loss for each grid was then calculated for each crop applying Equation 3, and using the crop-specific parameters and reference concentrations described in Table A2.2, and based on experimentally derived relationships between increasing O_3 concentrations and crop yield loss. Crop production loss was then calculated for each grid and aggregated to national- and regional-level values. Uncertainty ranges for RYL and CPL, based on the uncertainty in parameters a and b were derived by repeating the RYL and CPL calculations 1,000 times, each time replacing a and b with a value drawn from their probability distribution. The mean and 95% confidence intervals of crop production loss derived using the GISS and GEOS-Chem ozone exposure estimated were then calculated.

TABLE A2.2: SUMMARY OF PARAMETERS USED TO CALCULATE CROP IMPACTS

Crop	a (standard error)	b (standard error)	Reference concentration (ppb)	Reference
Maize	124 (2)	2.83 (0.23)	20	Lesser *et al.* 1990
Rice	202 (50)	2.47 (1.10)	25	Adams *et al*. 1989
Soy	107 (3)	1.58 (0.16)	20	Lesser *et al*. 1990
Wheat	137 (6)	2.34 (0.41)	25	Lesser *et al*. 1990

TABLE A2.3: MEASURES AND KEY FEATURES

Measure	Description	Maximum further potential assumed for 2030
Power sector		
Support to non-combustion renewables	Increased investments in renewable energy technology in the power sector to replace inefficient (mostly sub-critical) coal-fired power stations with non-combustion renewables (wind, solar, hydropower); Ban of new sub-critical plants	These measures could replace 450 units (150 gigawatts (GW)) of coal power plants
Phase-out/replacement of least efficient fossil fuel plants	Replacing coal use at the least efficient coal plants with efficient natural gas plants	These measures could replace 780 units (420 GW) of coal plants
Post-combustion controls	Post-combustion control of SO_2, NO_x and PM emissions of large boilers (flue gas desulphurization, selective catalytic reduction, dust filters) or equivalent emission limits	All new plants after 2020 Existing plants retrofitted by 2030
Industry		
Strong push on industrial energy efficiency	New or enhanced minimum energy efficiency standards	A 9% reduction in energy intensity compared to baseline, corresponding to 160 coal power plants (76 GW)
Post-combustion controls for large boilers	Post-combustion control of SO_2, NO_x and PM emissions of large boilers (flue gas desulphurization, selective catalytic reduction, dust filters)	All new plants after 2020 Existing plants retrofitted by 2030
Post-combustion controls for small industries	Emission limits for SO_2, NO_x, $PM_{2.5}$, depending on size, fuel and combustion process	All new plants after 2020
Industrial processes (steel, cement, etc.)	Best available techniques required for operating permits	All plants in 2030
Brick kilns	Modernization of brick kilns (Hoffmann kilns, Zig-zag kilns, vertical shaft brick kilns)	All new plants after 2020

TABLE A2.3: MEASURES AND KEY FEATURES (contd.)

Measure	Description	Maximum further potential assumed for 2030
Industry (contd.)		
Solvents industry, refineries	Low-solvent paints, incineration and recovery	Current practices in countries of the Organisation for Economic Co-operation and Development (OECD)
Mobile sources		
Improved public transport, urban planning	Enhanced public transport systems, complemented by bike sharing systems, bus rapid transit, etc. Stronger action to decrease car ownership	By 2030, improved public transport could reduce 10% of cars compared to the baseline
Gasoline cars	Introduction of Euro 6-equivalent emission standards, complemented by a maximum sulphur content of 10 ppm	All new cars as of 2020; no retrofits of existing vehicles
Diesel heavy-duty vehicles (trucks and buses)	Introduction of Euro 6-equivalent emission standards including diesel particle filters, complemented by a maximum sulphur content in diesel of 10 ppm	All new vehicles as of 2020; no retrofits of existing vehicles
Diesel light-duty vehicles (cars and delivery vans)	Introduction of Euro 6-equivalent emission standards including diesel particle filters, complemented by a maximum sulphur content in diesel of 10 ppm	All new cars as of 2020; no retrofits of existing vehicles
Non-road mobile machinery	Diesel particle filters for construction machinery, agricultural tractors and inland shipping, complemented by a maximum sulphur content in diesel of 10 ppm	All new equipment as of 2020; no retrofits of existing machinery
Two-wheelers	Phase-out two-stroke engine powered vehicles; replacement by four-stroke engines with strict emissions standards or electric engines	No new two-stroke engines after 2020
Strict inspection and maintenance (I&M) systems	Mandatory annual I&M to identify high-emitting vehicles and take them off the road; this will reduce NO_x, PM and VOC emissions	Effective I&M in place in 2030

TABLE A2.3: MEASURES AND KEY FEATURES (contd.)

Measure	Description	Maximum further potential assumed for 2030
Mobile sources (contd.)		
Electric vehicles	Electric cars	50% of cars in 2030
Maritime shipping	*Beyond the IMO agreement on sulphur content (which is part of the current legislation baseline):* liquid natural gas; diesel particle filters	For suitable new ships after 2020
Road paving and road cleaning	Enhanced paving and cleaning of roads and side-walks	For India, Indonesia, Iran, Nepal, Pakistan and Sri Lanka
Residential and commercial sector		
Strong push on residential energy efficiency	New or enhanced minimum energy performance standards for appliances, buildings, lighting, heating and cooling; roof-top solar installations, etc.	A 6% improvement in energy intensity, corresponding to 110 coal power plants (48 GW)
Clean cookstoves	**For cities:** full access to clean cooking fuels (natural gas, electricity); liquefied petroleum gas (LPG) will be shifted to rural areas **For rural areas:** use of LPG and solar power; remaining households will use advanced cookstoves, i.e., using processed biomass (pellets, more efficient stoves equipped with chimneys)	**For cities:** full access to natural gas and electricity by 2020 **For rural areas:** Full universal access to clean cooking facilities will be achieved by 2040 (10 years later than established in Sustainable Development Goal (SDG) 7); by 2030, 75% of current households will use LPG; the others advanced stoves
Coal briquettes for cooking	Replacement of chunk coal for cookstoves with briquettes	Full replacement by 2030
Agriculture		
Agricultural waste burning	Collection of agricultural waste and use for energetic purposes; ban on open burning of agricultural waste	Full ban enforced in 2030

TABLE A2.3 MEASURES AND KEY FEATURES (contd.)

Measure	Description	Maximum further potential assumed for 2030
Agriculture (contd.)		
Manure management	Measures to reduce CH_4 and NH_3 emissions from livestock production, including anaerobic digestion, covered storage of manure, efficient manure incorporation into soils, feeding strategies	Application potential is restricted by structural factors such as farm sizes, logistics, etc.
Urea application	Efficient application of urea and/or use of urease inhibitors; switch to ammonium nitrate fertilizers where applicable	Applicable to 50–80% of urea use in baseline
Rice paddies	Intermittent aeration of continuously flooded rice fields, combined with use of low CH_4 formation hybrids and sulphate containing amendments	Application to all continuously flooded rice fields in 2030
Forest fires	Prevention and forest management programmes, enforcement of anti-slash and burn programmes, etc.	About 30% reduction of air pollutant emissions in 2030
Energy production		
Coal mining	Pre-mining recovery of coal mine gas and ventilation air CH_4 oxidation technology installed on shafts from underground coal mines	All mines in 2030
Oil and gas production	Extended recovery of associated petroleum gas and leakage control of fugitive emissions from unintended leakage sources	All production in 2030
Waste management		
Management of solid waste	Centralized waste collection with source separation and treatment (recycling/biogas recovery/waste incineration with energy recovery), and limits on landfill disposal of organic waste	Full source separation and waste treatment by 2030
Residential waste burning	Centralized waste collection, disposal/incineration, ban on open burning	Full and effective ban in 2030

TABLE A2.3 MEASURES AND KEY FEATURES (contd.)

Measure	Description	Maximum further potential assumed for 2030
Waste management (contd.)		
Wastewater treatment	Well managed two-stage (anaerobic followed by aerobic) wastewater treatment with biogas recovery	By 2030, all current primary treatment facilities will be upgraded to two-stage systems
Refrigeration		
Ratification of the Kigali Amendment to the Montreal Protocol 2016	Phase-out of consumption of HFCs by 2050 in compliance with the Kigali Amendment	By 2030, about one third of the long-term potential

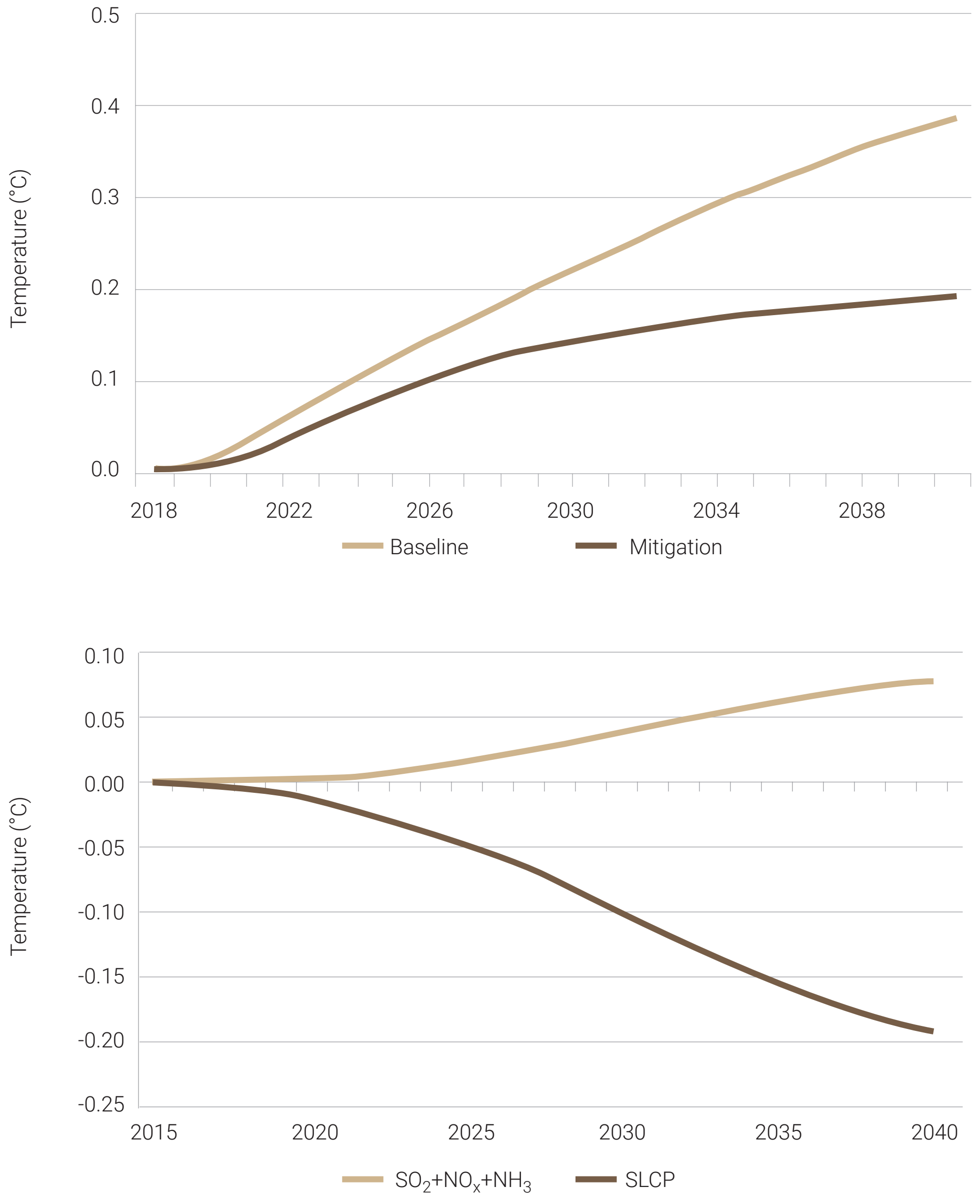
ANNEX 2.3 CLIMATE IMPACTS

Off-line temperature calculations using the absolute global temperature change potential (AGTP) method, using the same emission estimates from GAINS as an input, have been used to estimate the relative influence of different Asian emission scenarios on global temperature. The results are shown in Figure A2.9, where the impact on temperature of the mitigation scenario for different groups of substances, which aims to reduce air pollution in Asia while maximizing the contribution to achieving SDGs, is shown in relation to the temperature change in the baseline scenario.

The results are also shown for subsets of substances grouped according to those substances that cool the climate (SO_4, NO_X, and NH_3) and short-lived climate pollutants (SLCPs) that warm the climate (BC along with its co-emissions, and CH_4). It can be seen that the net average change in temperature is a reduction in warming (brown line), which is supported by the GCM runs, although the more simple climate calculations using AGTP show a change in warming of ~0.15°C 10 years earlier than using the GCM (Figure A2.10). However, using these calculations it can be seen that the air quality strategies reduce emissions of both cooling components and warming components. Differences between the sum of responses to cooling aerosols plus SLCPs and the total mitigation are attributable to CO_2 and HFCs. These finding are in line with those of the UNEP/World Meteorological Organization assessment in 2011. Additionally, Figure A2.9 shows the importance on concentrating on SLCP strategies alongside air quality strategies, and CO_2 strategies. This is because SO_2 will be reduced to protect air quality and as a result of a shift away from coal and oil, and to compensate for the potential increase in warming from the reduction of this cooling component in at the atmosphere, it is very important to concentrate efforts at the same time to promote reductions in short-lived warming components – primarily BC and CH_4.

The GISS Global Climate Model has also been run with the International Institute for Applied Systems Analysis (IIASA) emission baseline and mitigation scenario, with an ensemble of three simulations performed over a long period from 2006 to 2054, and the average result of the mitigation scenario relative to the baseline is shown in Figure A2.10. This figure shows the resulting global temperature change of mitigating air pollution (specifically $PM_{2.5}$), CO_2 (according to the policy scenario from IIASA), and other greenhouse gases such as CH_4 and HFCs, relative to the baseline scenario. Initially there seems to be a slight increase in global temperature, although this is not a significant change, and then there is a significant decrease in global temperature by 2050, of about 0.2°C, which is a substantial reduction in global temperature over this time frame for emission changes in only one world region. The initial warming is consistent with prior studies looking at the impact of measures controlling large-scale energy and transport sector emissions that affect both short-lived cooling agents and long-lived warming agents (Shindell *et al*. 2016; Raes and Seinfeld 2009).

Similarly, as the cooling aerosols that are reduced by the policies are predominantly local whereas the reductions in the greenhouse gases CO_2 and CH_4 are spread worldwide, the climate benefits in terms of reduced warming tend to be weakest over Asia itself (Figure A2.11). Similar results were found for

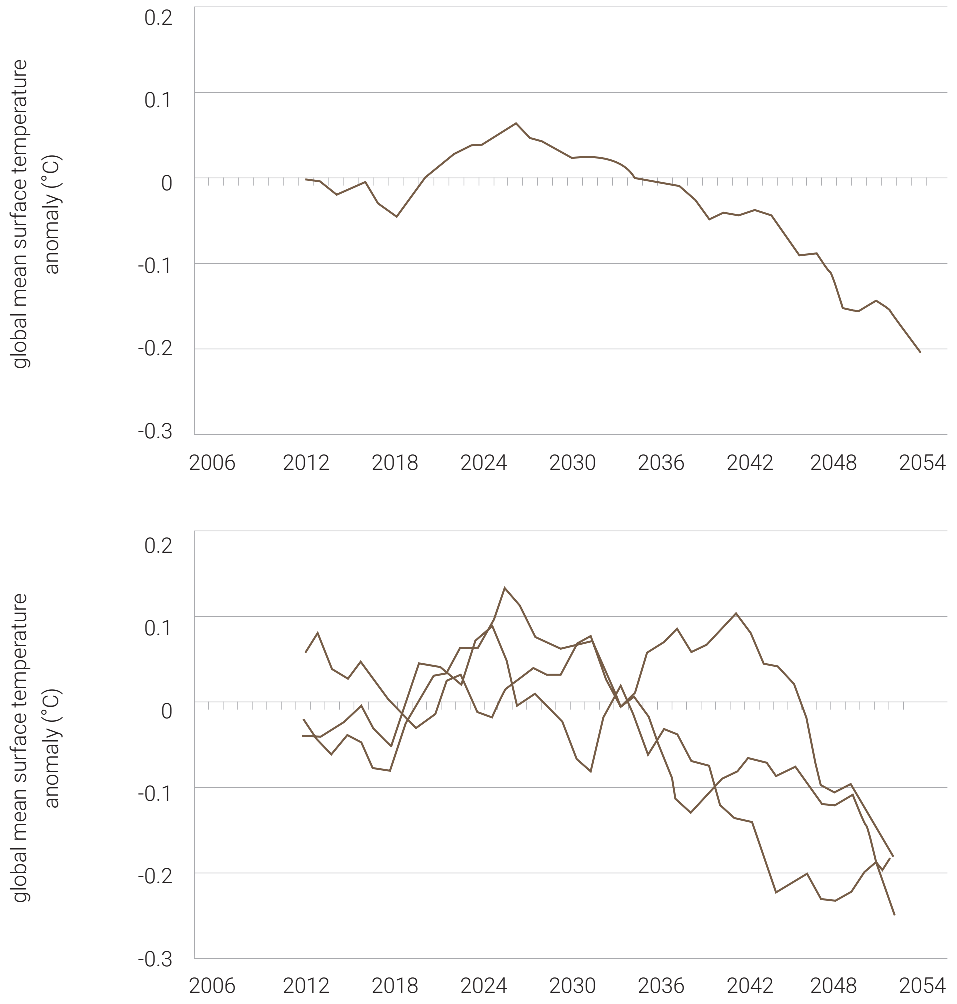


Note: Impacts of all substances acting together are shown in the upper panel (except VOCs, which are not well-suited to the AGTP analysis), whereas the impact of the cooling substances primarily associated with power generation, industry and gasoline-powered vehicles, and of SLCPs (BC, OC and CO primarily from incomplete combustion of residential fuels and diesel vehicles, and CH_4 (but not HFCs)) are grouped together and compared in the lower panel.

FIGURE A2.8 IMPACT OF THE AIR POLLUTION AND SUSTAINABLE DEVELOPMENT GOAL ATTAINMENT MITIGATION SCENARIO ON WARMING, ESTIMATED USING ABSOLUTE GLOBAL TEMPERATURE POTENTIALS

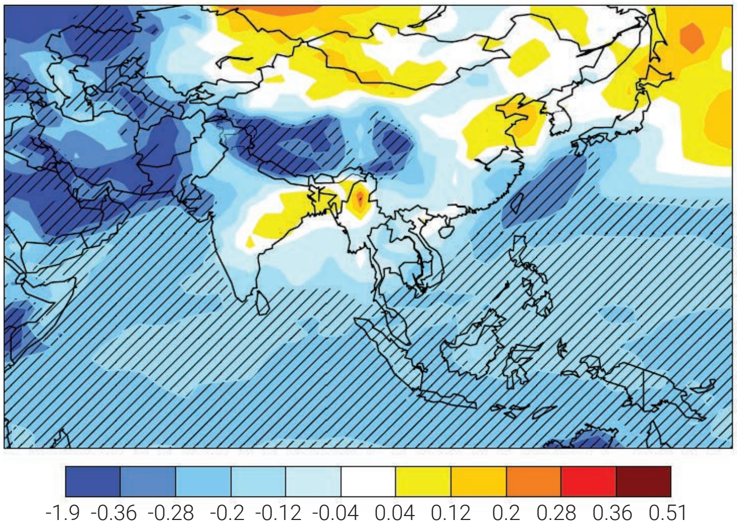
United States policies that simultaneously reduce long-lived greenhouse gases and short-lived cooling aerosols (Shindell *et al*. 2016). The exception in the case of Asia is the Himalayan/Tibetan Plateau region, where, owing to the strong snow/ice albedo effects of reductions in BC deposited on the surface as well as the greater importance of BC relative to cooling aerosols over bright surfaces, there is a significant local cooling (Figure A2.11). This has the potential to substantially reduce melting of glaciers in this region. It should also be noted that although the climate benefits of action taken to reduce both cooling aerosols and long-lived warming greenhouse gases is in general weakest in a region taking action on its own, such actions taken broadly across major regions of the world would lead to everywhere receiving benefits, as the global greenhouse gas benefits from multiple regions would outweigh the local disbenefits of reductions in cooling aerosols – in addition, of course, to the large local public health benefits in regions that reduce cooling aerosols.

The temperature change in Figure A2.10 is the net result of changes in all of the emissions affecting atmospheric temperature. Given that we were only able to run the GCM for two scenarios (the current legislation baseline and the 25 clean air measures scenario) it was not possible to show the relative impact of abating different sources and substances in a number of different scenarios.



Note: Eight-year running mean values are shown for the ensemble mean (top) and for the three individual ensemble members (bottom).

FIGURE A2.9: GLOBAL MEAN SURFACE TEMPERATURE CHANGE DUE TO THE MITIGATION SCENARIO RELATIVE TO THE BASELINE SCENARIO (°C) BETWEEN 2015 AND 2054



Note: The stripes indicate significant changes (95 per cent confidence).

Note: Hatching indicates values that are statistically significant at the 95% confidence level.

FIGURE A2.10 GEOGRAPHIC PATTERN OF ANNUAL AVERAGE SURFACE TEMPERATURE RESPONSE TO IMPLEMENTATION OF THE 25 CLEAN AIR MEASURES, AVERAGED OVER THE THREE ENSEMBLE MEMBERS FOR THE 2046–2054 DECADE


←01E
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REFERENCES

REFERENCES

Chapter 1

Abrol, Y.P., Adhya, T.K., Aneja, V.P., Raghuram, N., Pathak, H., Kulshrestha, U., Sharma, C. and Sing, B. (2017). *The Indian Nitrogen Assessment: Sources of Reactive Nitrogen, Environmental and Climate Effects, Management Options, and Policies.* Elsevier, Amsterdam, Netherlands.

ADB (2015). *Climate Change Resilience in Asia's Cities.* Asian Development Bank, Manila, Philippines. www.adb.org/news/infographics/climate-change-resilience-asias-cities

ADB (2012). *The State of Pacific Towns and Cities: Urbanization in ADB's Pacific Developing Member Countries.* Asian Development Bank, Manila, Philippines. www.adb.org/sites/default/files/publication/29765/state-pacific-towns-cities.pdf

Agrawal, S.B., Singh, A. and Rathore, D. (2005). Role of ethylene diurea (EDU) in assessing impact of ozone on *Vigna radiata* L. plants in a suburban area of Allahabad (India). *Chemosphere*, 61(2), 218–228: doi.org/10.1016/j.chemosphere.2005.01.087.

Agrawal, M., Singh, B., Rajput, M., Marshall, F. and Bell, J.N.B. (2003). Effect of air pollution on peri-urban agriculture: a case study. *Environmental Pollution*, 126, 323–329.

Ahmad, M.N., Büker, P., Khalid, S., Berg, L.V.D., Shah, H.U., Wahid, A., Emberson, L., Power, S.A. and Ashmore, M. (2013). Effects of ozone on crops in north-west Pakistan. Environmental Pollution, 174, 244–249.

Ainsworth, E.A. (2016). Understanding and improving global crop response to ozone pollution. *The Plant Journal*, 90(5), 835–1025. doi:10.1111/tpj.13298.

Ainsworth E.A. and Rogers, A. (2007). The response of photosynthesis and stomatal conductance to rising CO_2: mechanisms and environmental interactions. *Plant, Cell & Environment*, 30, 258–270.

Ainsworth, E.A., Yendrek, C.R., Sitch, S., Collins, W.J. and Emberson, L.D. (2012). The effects of tropospheric ozone on net primary productivity and implications for climate change. *Annual Review of Plant Biology*, 63, 637–661.

Akimoto, H., Kurokawa, J., Sudo, K., Nagashima, T., Takemura, T., Klimont. Z., Amann, M. and Suzuki, K.(2015). SLCP co-control approach in East Asia: tropospheric ozone reduction strategy by simultaneous reduction of NOx/NMVOC and methane. *Atmospheric Environment*, 122, 588–95.

Akhtar, N., Yamaguchi, M., Inada, H., Hoshino, D., Kondo, T. and Izuta, T. (2010). Effects of ozone on growth, yield and leaf gas exchange rates of two Bangladeshi cultivars of wheat (*Triticum aestivum* L.). *Environmental Pollution*, 158, 1763–1767.

Allen, M.R. and Ingram, W.J. (2002). Constraints on future changes in climate and the hydrologic cycle. *Nature*, 419, 224–32.

Allen, R.J., Landuyt, W. and Rumbold, S.T. (2016). An increase in aerosol burden and radiative effects in a warmer world. *Nature Climate Change*, 6, 269–74.

Amegah, A.K., Quansah, R. and Jaakkola, J.J.K. (2014). Household air pollution from solid fuel use and risk of adverse pregnancy outcomes: a systematic review and meta-analysis of the empirical evidence. *PLoS ONE*, 9(12), e113920.

Anderson, J.O., Thundiyil, J.G. and Stolbach, A. (2012). Clearing the air: a review of the effects of particulate matter air pollution on human health. *J Med Toxicol*, 8(2), 166–75.

Andreae, M.O., Jones, C.D. and Cox, P.M. (2005). Strong present-day aerosol cooling implies a hot future. *Nature*, 435, 1187–90.

Andrews, T., Forster, P.M., Boucher, O., Bellouin, N. and Jones, A. (2010). Precipitation, radiative forcing and global temperature change. *Geophysical Research Letters*, 37. doi.org/10.1029/2010GL043991.

APERC (2016). *APEC Energy Demand and Supply Outlook*, 6th edition. Asia Pacific Energy Research Centre, Tokyo, Japan. http://aperc.ieej.or.jp/file/2016/5/10/APEC_Outlook6th_VolumeI.pdf

Archer, D., Eby, M., Brovkin, V., Ridgwell, A., Cao, L., Mikolajewicz, U., Caldeira, K., Matsumoto, K., Munhoven, G., Montenegro, A. and Tokos, K. (2009). Atmospheric lifetime of fossil fuel carbon dioxide. *Annual Review of Earth and Planetary Sciences*, 37, 117–34.

Ariyaphanphitak, W., Chidthaisong, A., Sarobol, E., Bashkin, V.N. and Towprayoon, S. (2005). Effects of elevated ozone concentrations on Thai Jasmine rice cultivars (*Oryza sativa* L.). *Water Air and Soil Pollution*, 167(1–4), 179–200.

Arku, R.E., Birch, A., Shupler, M., Yusuf, S., Hystad, P. and Brauer, M. (2018). Characterizing exposure to household air pollution within the Prospective Urban Rural Epidemiology (PURE) study. *Environment International*, 114, 307–317.

Armour, K.C. and Roe, G.H. (2011). Climate commitment in an uncertain world. *Geophysical Research Letters*, 38. doi.org/10.1029/2010GL045850

Armstrong, J.R.M. and Campbell, H. (1991). Indoor air pollution exposure and lower respiratory infections in young Gambian children. *International Journal of Epidemiology*, 20(2), 424–429, https://doi.org/10.1093/ije/20.2.424.

Arneth, A., Harrison, S.P., Zaehle, S., Tsigaridis, K., Menon, S., Bartlein, P.J., Feichter, J., Korhola, A., Kulmala, M., O'Donnell, D., Schurgers, G., Sorvari, S. and Vesala, T. (2010). Terrestrial biogeochemical feedbacks in the climate system. *Nature Geoscience*, 3, 525–32.

ASEAN (2018). Haze Action Online. Association of Southeast Asian Nations, Jakarta, Indonesia. http://haze.asean.org

Atkinson, R.W., Butland, B.K., Dimitroulopoulou, C., Heal, M.R., Stedman, J.R., Carslaw, N., Jarvis, D., Heaviside C., Vardoulakis, S., Walton, H. and Anderson, H.R. (2016). Long-term exposure to ambient ozone and mortality: a quantitative systematic review and meta-analysis of evidence from cohort studies. *British Medical Journal Open*, 6, e009493. doi:10.1136/bmjopen-2015-009493.

Atkinson, R.W., Cohen, A., Mehta, S. and Anderson, H.R. (2011). Systematic review and meta-analysis of epidemiological time-series studies on outdoor air pollution and health in Asia. *Air Quality, Atmosphere & Health*, 5(4), 383–391.

Aunan, K., Berntsen, T.K. and Seip, H.M. (2000). Surface ozone in China and its possible impact on agricultural crop yields. *Ambio*, 29, 294–301.

Avnery, S., Mauzerall, D.L., Liu, J. and Horowitz, L.W. (2011). Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage. *Atmospheric Environment*, 45, 2284–2296.

Babadjouni, R.M., Hodis, D.M., Radwanski, R., Durazo, R., Patel, A., Liu, Q., Mack, W.J. (2017). Clinical effects of air pollution on the central nervous system; a review. *Journal of Clinical Neuroscience*, 43, 16–24. doi:10.1016/j.jocn.2017.04.028.

Babu, S.S., Chaubey, J.P., Krishna Moorthy, K., Gogoi, M.M., Kompalli, S.K., Sreekanth, V., Bagare, S.P., Bhatt, B.C., Gaur, V.K., Prabhu, T.P. and Singh, N.S. (2011). High altitude (≈4520 m amsl) measurements of black carbon aerosols over western trans-Himalayas: seasonal heterogeneity and source apportionment. *Journal of Geophysical Research: Atmospheres*, 116(24), 1–15. doi:10.1029/2011JD016722.

Bai, Y.F., Wu, J.G., Clark, C.M., Naeem, S., Pan, Q.M., Huang, J.H., Zhang, L.X., Han, X.G. (2010). Tradeoffs and thresholds in the effects of nitrogen addition on biodiversity and ecosystem functioning: evidence from inner Mongolia grasslands. *Global Change Biology*, 16, 358e372.

Balakrishnan, K., Ghosh, S., Thangavel, G., Sambandam, S., Mukhopadhyay, K., Puttaswamy, N., Sadasivam, A., Ramaswamy, P., Johnson, P., Kuppuswamy, R., Natesan, D., Maheshwari, U., Natarajan, A., Rajendran, G., Ramasami, R., Madhav, S., Manivannan, S., Nargunanadan, S., Natarajan, S., Saidam, S., Chakraborty, M., Balakrishnan, L. and Thanasekaraan, V. (2017). Exposures to fine particulate matter ($PM_{2.5}$) and birthweight in a rural-urban, mother-child cohort in Tamil Nadu, India. *Environmental Research*, 161, 524–531.

Balakrishnan, K., Ghosh, S., Ganguli, B., Sambandam, S., Bruce, N., Barnes, D.F. and Smith, K.R. (2013a). State and national household concentrations of $PM_{2.5}$ from solid cookfuel use: results from measurements and modeling in India for estimation of the global burden of disease. *Environmental Health*, 12, 77.

Balakrishnan, K., Bhaswati Ganguli, B., Ghosh, S., Sambandam, S., Roy, S.S. and Chatterjee, A. (2013b). A spatially disaggregated time-series analysis of the short-term effects of particulate matter exposure on mortality in Chennai, India. *Air Quality, Atmosphere and Health*, 6(1), 111–121.

Balakrishnan, K., Ramaswamy, P., Sambandam, S., Thangavel, G., Ghosh, S., Johnson, P., Mukhopadhyay, K., Venugopal, V. and Thanasekaraan, V. (2011). Air pollution from household solid fuel combustion in India: an overview of exposure and health related information to inform health research priorities. *Global Health Action*, 4.

Barnett, T.P., Adam J.C. and Lettenmaier, D.P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438, 303–309. doi:10.1038/nature04141.

Barratt, O. (2016). Haze episode cost Singapore estimated S$700m last year. *Channel News Asia*. Mediacorp, Singapore. http://www.channelnewsasia.com/news/singapore/haze-episode-cost-singapore-estimated-s-700m-last-year-masagos-8147924.

Behera, S.N., Sharma, M., Aneja, V.P. and Balasubramanian, R. (2013). Ammonia in the atmosphere: a review on emission sources, atmospheric chemistry and deposition on terrestrial bodies. *Environmental Science and Pollution Research*, 20, 8092–131.

Bell, J.N.B., Power, S.A., Jarraud, N., Agrawal, M. and Davies, C. (2011). The effects of air pollution on urban ecosystems and agriculture. *International Journal of Sustainable Development & World Ecology*, 18(3), 226–235.

Bergin, M.H., Greenwald, R., Xu, J., Berta, Y. and Chameides, W.L. (2001). Influence of aerosol dry deposition on photosynthetically active radiation available to plants: a case study in the Yangtze delta region of China. *Geophysical Research Letters*, 28, 3605–3608.

Berntsen, T., Tanaka, K. and Fuglestvedt, J. (2010). Does black carbon abatement hamper CO_2 abatement? *Climate Change*, 103, 627–33.

Berntsen, T., Fuglestvedt, J., Myhre, G., Stordal, F. and Berglen, T.F. (2006). Abatement of greenhouse gases: does location matter? *Climate Change*, 74, 377–411.

Bloomfield, E. and Malla, M.B. (2015). *Gender and Livelihoods Impacts of Clean Cookstoves in South Asia Study*. Global Alliance for Clean Cookstoves, Washington, DC, USA. http://cleancookstoves.org/resources/357.html

Bobbink, R., Hicks, K., Galloway, J., Spranger, T., Alkemade, R., Ashmore, M., Bustamante, M., Cinderby, S., Davidson, E., Dentener, F., Emmett, B., Erisman, J.W., Fenn, M., Gilliam, F., Nordin, A., Pardo, L. and de Vries, W. (2010). Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. *Ecological Applications*, 20(1), 30–59.

Bolch, T., Kulkarni, A., Kaab, A., Huggel, C., Paul, F., Cogley, J.G., Frey, H., Kargei, J.S., Fujita, K., Scheel, M., Bajracharya, S. and Stoffel, M. (2012). The state and fate of Himalayan glaciers. *Science*, 336, 6079.

Bond, T.C., Doherty, S.J., Fahey, D.W., Forster, P.M., Berntsen, T., DeAngelo, B.J., Flanner, M.G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P.K., Sarofim, M.C., Schultz, M.G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S.K., Hopke, P.K., Jacobson, M.Z., Kaiser, J.W., Klimont, Z., Lohmann, U., Schwarz, J.P., Shindell, D., Storelvmo, T., Warren. S.G. and Zender, C.S. (2013). Bounding the role of black carbon in the climate system: a scientific assessment. *Journal of Geophysical Research: Atmospheres*, 118, 5380–552.

Bonjour, S., Adair-Rohani, H., Wolf, J., Bruce, N.G., Mehta, S., Prüss-Ustün, A., Lahiff, M., Rehfuess, E.A., Mishra, V. and Smith, K.R. (2013). Solid fuel use for household cooking: country and regional estimates for 1980–2010. *Environmental Health Perspectives*, 121(7), 784–90.

Boucher, O., Randall, D., Artaxo, P., Bretherton, C., Feingold, G., Forster, P., Kerminen, V-M., Kondo, Y., Liao, H., Lohmann, U., Rasch, P., Satheesh, S.K., Sherwood, S., Stevens, B. and Zhang, X.Y. (2013). Climate Change 2013: *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, pp 571–658. [T.F. Stocker, Qin, D., Plattner, G-K. *et al*. (eds.)]. Cambridge University Press, Cambridge, UK.

Brauer, M., Freedman, G., Frostad, J., van Donkelaar, A., Martin, R.V., Dentener, F., van Dingenen, R., Estep, K., Amini, H., Apte, J.S., Balakrishnan, K., Barregard, L., Broday, D., Feigin, V., Ghosh, S., Hopke, P.K., Knibbs, L.D., Kokubo, Y., Liu, Y., Ma, S., Morawska, L., Texcalac Sangrador, J.L., Shaddick, G., Anderson, H.R., Vos, T., Forouzanfar, M.H., Burnett, R.T. and Cohen, A. (2016). Ambient air pollution exposure estimation for the Global Burden of Disease 2013. *Environmental Science & Technology*, 50(1), 79–88.

Brauer, M., Amann, M., Burnett, R.T., Cohen, A., Dentener, F., Ezzati, M., Henderson, S.B., Krzyzanowski, M., Martin, R.V., Van Dingenen, R., van Donkelaar, A. and Thurston, G.D. (2012). Exposure assessment for estimation of the global burden of disease attributable to outdoor air pollution. *Environmental Science & Technology*, 46(2), 652–60.

Brockmeyer, S. and D’Angiulli, A. (2016). How air pollution alters brain development: the role of neuroinflammation. *Translational Neuroscience*, 7, 24–30.

Burney, J. and Ramanathan, V. (2014). Recent climate and air pollution impacts on Indian agriculture. *Proceedings of the National Academies of Science of the United States of America*, 111(46), 16319–16324.

Burnett, R.T., Pope, C.A. III., Ezzati, M., Olives, C., Lim, S.S., Mehta, S., Shin, H.H., Singh, G., Hubbell, B., Brauer, M., Anderson, H,R., Smith, K.R., Balmes, J.R., Bruce, N.G., Kan, H., Laden, F., Prüss-Ustün, A., Turner, C., Gapstur, S.M., Diver, W.R. and Cohen, A. (2014). An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environmental Health Perspectives*, 122(4), 397–403.

Butt, E.W., Rap, A., Schmidt, A., Scott, C.E., Pringle, K.J., Reddington, C.L., Richards, N.A.D., Woodhouse, M.T., Ramirez-Villegas, J., Yang, H., Vakkari, V., Stone, E.A., Rupakheti, M., Praveen, P.S., van Zyl, P.G., Beukes, J.P., Josipovic, M., Mitchell, E.J.S., Sallu, S.M., Forster, P.M. and Spracklen, D.V. (2016). The impact of residential combustion emissions on atmospheric aerosol, human health, and climate. *Atmospheric Chemistry and Physics*, 16(2), 873–905. doi:10.5194/acp-16-873-2016.

Cacciottolo, M., Wang, X., Driscoll, I., Woodward, N., Saffari, A., Reyes, J., Serre, M.L., Vizuete, W., Sioutas, C., Morgan, T.E., Gatz, M., Chui, H.C., Shumaker, S.A., Resnick, S,M., Finch, C.E. and Chen, J.C. (2017). Particulate air pollutants, APOE alleles and their contributions to cognitive impairment in older women and to amyloidogenesis in experimental models. *Translational Psychiatry*, 7, e1022.

CAI-Asia (2010). *Air Quality in Asia: Status and Trends*, 2010 edition. Clean Air Initiative for Asian Cities (CAI-Asia) Center, Pasig, Philippines. http://cleanairasia.org/wp-content/uploads/portal/files/documents/AQ_in_Asia.pdf

Cai, W., Li, K., Liao, H., Wang, H. and Wu, L. (2017). Weather conditions conducive to Beijing severe haze more frequent under climate change. *Nature Climate Change*, 7, 257–262. doi:10.1038/nclimate3249.

Carslaw, K.S., Lee, L.A., Reddington, C.L., Pringle, K.J., Rap, A., Forster, P.M., Mann, G.W., Spracklen, D.V., Woodhouse, M.T., Regayre, L.A. and Pierce, J.R. (2013). Large contribution of natural aerosols to uncertainty in indirect forcing. *Nature*, 503, 67–71.

Casanova, R., Wang, X., Reyes, J., Akita, Y., Serre, M.L., Vizuete, W., Chui, H.C., Driscoll, I., Resnick, S.M., Espeland, M.A. and Chen, J-C. (2016). A voxel-based morphometry study reveals local brain structural alterations associated with ambient fine particles in older women. *Frontiers in Human Neuroscience*, 10, 495.

CCAC (2017). *Metrics for Accounting for SLCPs Mitigation Benefits: Discussion Paper for the CCAC*. SAP Expert Workshop on Metrics, Ottawa, Canada.

Chae, Y. and Park, J. (2011). Quantifying costs and benefits of integrated environmental strategies of air quality management and greenhouse gas reduction in the Seoul Metropolitan Area. *Energy Policy*, 39(9), 5296–5308.

Chafe, Z.A., Brauer, M., Klimont, Z., Van Dingenen, R., Mehta, S., Rao, S., Riahi, K., Dentener, F. and Smith, K.R. (2014). Household cooking with solid fuels contributes to ambient $PM_{2.5}$ air pollution and the burden of disease. *Environmental Health Perspectives*, 122(12), 1314–20. doi:10.1289/ehp.1206340.

Chaudhary, N. and Agrawal, S, B, (2015). The role of elevated ozone on growth, yield and seed quality amongst six cultivars of mung bean. *Ecotoxicology and Environmental Safety*, 111, 286–294.

Chaudhary, N., Singh, S., Agrawal, S.B. and Agrawal, M. (2013). Assessment of six Indian cultivars of mung bean against ozone by using foliar injury index and changes in carbon assimilation, gas exchange, chlorophyll fluorescence and photosynthetic pigments. *Environmental Monitoring and Assessment*, 185, 7793–7807.

Chen, R., Yin, P., Meng, X., Liu, C., Wang, L., Xu, X., Ross, J.A., Tse, L.A., Zhao, Z., Kan, H. and Zhou, M. (2017a). Fine particulate air pollution and daily mortality: a nationwide analysis in 272 Chinese cities. *American Journal of Respiratory and Critical Care Medicine*, 196(1), 73–81.

Chen, H., Kwong, J.C., Copes, R., Tu, K., Villeneuve, P.J., van Donkelaar, A., Martin, R.V., Murray, B.J., Jessiman, B., Wilton, A.S., Kopp, A. and Burnett, R.T. (2017b). Living near major roads and the incidence of dementia, Parkinson's disease, and multiple sclerosis: a population-based cohort study. *Lancet*, 389 (10070), 718–726.

Chen, J., Zeng, Q., Zhu, J.-G., Liu, G., Cao, J.-L., Xie, Z.-B., Tang, H.-Y. and Kazuhiko, K. (2011). Nitrogen supply mitigates the effects of elevated [O_3] on photosynthesis and yield in wheat. *Journal of Plant Ecology*, 35, 523–530 (in Chinese).

Cheng, S.J., Bohrer, G., Steiner, A.L., Hollinger, D.Y., Suyker, A., Phillips, R.P. and Nadelhoffer, K.J. (2015). Variations in the influence of diffuse light on gross primary productivity in temperate ecosystems. *Agricultural and Forest Meteorology*, 201, 98–110.

Cherubini, F. and Tanaka, K. (2016). Amending the inadequacy of a single indicator for climate impact analyses. *Environmental Science & Technology*, 50, 12530–1.

Cherubini, F., Fuglestvedt, J., Gasser, T., Reisinger, A., Cavalett, O., Huijbregts, M.A.J., Johansson, D.J.A., Jørgensen, S.V., Raugei, M., Schivley, G., Strømman, A.H., Tanaka, K. and Levasseur, A. (2016). Bridging the gap between impact assessment methods and climate science. *Environmental Science & Policy*, 64, 129–40.

Chuwah, C., Noije, T.V., Vuuren, D.P.V., Stehfest, E. and Hazeleger, W. (2015). Global impacts of surface ozone changes on crop yields and land use. *Atmospheric Environment*, 106, 11–23.

Clark, M.L., Peel, J.L., Balakrishnan, K., Breysse, P.N., Chillrud, S.N., Naeher, L.P., Rodes, C.E., Vette, A.F. and Balbus, J.M. (2013). Health and household air pollution from solid fuel use: the need for improved exposure assessment. *Environmental Health Perspectives*, 121(10), 1120–8.

Clifford, A., Lang, L., Chen, R., Anstey, K.J. and Seaton, A. (2016). Exposure to air pollution and cognitive functioning across the life course – a systematic literature review. *Environmental Research*, 147, 383–398. doi:10.1016/j.envres.2016.01.018.

Clougherty, J.E., Souza, K. and Cullen, M.R. (2010). Work and its role in shaping the social gradient in health. *Annals of the New York Academy of Sciences*, 1186, 102–24. doi:10.1111/j.1749-6632.2009.05338.x.

Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope, C.A. III., Shin, H., Straif, K., Shaddick, G., Thomas, M., Van Dingenen, R., van Donkelaar, A., Vos, T., Murray, C.J.L. and Forouzanfar, M.H. (2017). Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *Lancet*, 389, 1907–1918. doi:10.1016/S0140-6736(17)30505-6.

Collins, W.J., Fry, M.M., Yu, H., Fuglestvedt, J.S., Shindell, D.T. and West, J.J. (2013). Global and regional temperature-change potentials for near-term climate forcers. *Atmospheric Chemistry and Physics*, 13, 2471–85.

Conibear, L., Butt, E.W., Knote, C., Arnold, S.R. and Spracklen, D.V. (2018). Residential energy use emissions dominate health impacts from exposure to ambient particulate matter in India. *Nature Communications*, 9(1), 1–9. doi:10.1038/s41467-018-02986-7.

Cosselman, K.E., Navas-Acien, A. and Kaufman, J.D. (2015). Environmental factors in cardiovascular disease. *Nature Reviews Cardiology*, 12(11), 627–42.

Cowan, T., and Cai, W. (2011). The impact of Asian and non-Asian anthropogenic aerosols on 20th century Asian summer monsoon. *Geophysical Research Letters*, 38, L11703. doi:10.1029/2011GL047268.

Crane, K. and Mao, Z. (2015). *Costs of Selected Policies to Address Air Pollution in China*. Rand Corporation, Santa Monica, CA, USA. https://www.rand.org/content/dam/rand/pubs/research_reports/RR800/RR861/RAND_RR861.pdf

Crossley, A. and Fowler, D. (1986). The weathering of Scots pine epicuticular wax in polluted and clean air. *New Phytologist*, 103, 207–218.

Danh, N.T., Huy, L.N. and Kim Oanh, N.T. (2016). Assessment of rice yield loss due to exposure to ozone pollution in southern Vietnam. *Science of the Total Environment*, 566–567, 1069–1079.

Deckmyn, G., de Beeck, M., Löw, M., Then, C., Verbeeck H., Wipfler, P. and Ceulemans, R. (2008). Modelling ozone effects on adult beech trees through simulation of defense, damage and repair costs: implementation of the CASIROZ ozone model in the ANAFORE forest model. *Plant Biology*. doi.org/10.1055/s-2006-924762.

Dehghan, S.K. (2016). Tehran shuts schools as thick smog is linked to hundreds of deaths. *The Guardian*. www.theguardian.com/world/2016/nov/15/tehran-shuts-schools-thick-smog-kills-hundreds-people-iran

Dentener, F., Stevenson, D., Ellingsen, K., van Noije, T., Schultz, M., Amann, M., Atherton, C., Bell, N., Bergmann, D., Bey, I., Bouwman, L., Butler, T., Cofala, J., Collins, B., Drevet, J., Doherty, R., Eickhout, B., Eskes, H., Fiore, A., Gauss, M., Hauglustaine, D., Horowitz, L., Isaksen, I.S.A., Josse, B., Lawrence, M., Krol, M., Lamarque, J.F., Montanaro, V., Müller, J.F., Peuch, V.H., Pitari, G., Pyle, J., Rast, S., Rodriguez, J., Sanderson, M., Savage, N.H., Shindell, D., Strahan, S., Szopa, S., Sudo, K., Van Dingenen, R., Wild, O. and Zeng, G. (2006). The global atmospheric environment for the next generation. *Environmental Science & Technology*, 40, 3586–3594. doi:10.1021/es0523845.

Dholakia, H.H., Bhadra, D. and Garg, A. (2014). Short term association between ambient air pollution and mortality and modification by temperature in five Indian cities. *Atmospheric Environment*, 99, 168–174.

Doherty, S.J., Grenfell, T.C., Forsstrom, S., Hegg, D.L., Brandt, R.E. and Warren, S.G. (2013). Observed vertical redistribution of black carbon and other insoluble light absorbing particles in melting snow. *Journal of Geophysical Research: Atmospheres*, 118, 5553–5569. doi.org/10.1002/jgrd.50235.

Du, E., de Vries, W., Han, W., Liu, X.J., Yan, Z.B., and Jiang, Y. (2016). Imbalanced phosphorus and nitrogen deposition in China's forests. *Atmospheric Chemistry and Physics*, 16, 8571–8579.

Duan, L., Yu, Q., Zhang, Q., Wang, Z., Pan, Y., Larssen, T., Tang, J. and Mulder, J. (2016). Acid deposition in Asia: emissions, deposition, and ecosystem effects. *Atmospheric Environment*, 146, 55–69. doi.org/10.1016/j.atmosenv.2016.07.018.

EANET (2016). *The Third Periodic Report on the State of Acid Deposition in East Asia, Part II: National Assessments*. Acid Deposition Monitoring Network in East Asia (EANET). Asia Center for Air Pollution Research, Japan. http://www.eanet.asia/product/PRSAD/3_PRSAD/3_PRSAD2.pdf

EEA (2014). *Effects of Air Pollution on European Ecosystems: Past and Future Exposure of European Freshwater and Terrestrial Habitats to Acidifying and Eutrophying Air Pollutants*. EEA Technical report No. 11/2014. European Environment Agency, Copenhagen, Denmark.

EIU (2016). *Global Liveability Ranking 2016*. Economist Intelligence Unit, London, UK. www.eiu.com/public/topical_report.aspx?campaignid=liveability2016

Emberson, L.D., Pleijel, H., Ainsworth, L., Van den Berg, M., Ren, W., Osborne, S.A., Mills, G., Pandey, D., Dentener, F., Bueker, P., Ewert, F., Koeble, R. and Van Dingenen, R. (2018). Ozone effects on crops and consideration in crop models. *European Journal of Agronomy*. doi:10.1016/j.eja.2018.06.002.

Emberson, L.D., Büker, P., Ashmore, M.R., Mills, G., Jackson, L.S., Agrawal, M., Atikuzzaman, M.D., Cinderby, S., Engardt, M., Jamir, C., Kobayashi, K., Oanh, N.K.T., Quadir, Q.F. and Wahid, A. (2009). A comparison of North American and Asian exposure-response data for ozone effects on crop yields. *Atmospheric Environment*, 43(12), 1945–1953. doi.org/10.1016/j.atmosenv.2009.01.005.

Enjie, L., Endter-Wada, J. and Li, S. (2015). Characterizing and contextualizing the water challenges of megacities. *Journal of the American Water Resources Association (JAWRA)*, 51(3), 589-613. doi:10.1111/1752-1688.12310.

ESA (2002). *Nature Highlights Use of Space Imagery to Study Indonesian Fires*. European Space Agency, Paris, France. www.esa.int/Our_Activities/Observing_the_Earth/i_Nature_i_highlights_use_of_space_imagery_to_study_Indonesian_fires.

Eze, I.C., Hemkens, L.G., Bucher, H.C., Hoffmann, B., Schindler, C., Kunzli, N., Schikowski, T. and Probst-Hensch, N.M. (2015). Association between ambient air pollution and diabetes mellitus in Europe and North America: systematic review and meta-analysis. *Environmental Health Perspectives*, 123, 381–389. doi:10.1289/ehp.1307823.

Fan, H.B., Liu, W.F., Yan-Yan, L.I., Liao, Y.C. and Yuan, Y.H. (2007). Tree growth and soil nutrients in response to nitrogen deposition in a subtropical Chinese fir plantation. *Acta Ecologica Sinica*, 27, 4630e4642 (in Chinese).

Fang, Y.T., Gundersen, P., Mo, J.M. and Zhu, W.X. (2009). Nitrogen leaching in response to increased nitrogen inputs in subtropical monsoon forests in southern China. *Forest Ecology and Management*, 257, 332e342.

Fang, Y.T., Koba, K., Makabe, A., Takahashi, C., Zhu, W.X., Hayashi, T., Hokari, A.A., Urakawa, R., Bai, E., Houlton, B.Z., Xi, D., Zhang, S., Matsushita, K., Tu, Y., Liu, D., Zhu, F., Wang, Z., Zhou, G., Chen, D., Makita, T., Toda, H., Liu, X., Chen, Q., Zhang, D., Li, Y. and Yoh, M. (2015). Microbial denitrification dominates nitrate losses from forest ecosystems. *Proceedings of the National Academy of Sciences of the USA*, 112, 1470e1474.

Fangmeier, A., Brockerhoff, U., Grüters, U. and Jäger, H.J. (1994). Growth and yield responses of spring wheat (Triticum aestivum L. CV. Turbo) grown in open-top chambers to ozone and water stress. *Environmental Pollution*, 83(3), 317–25.

Felzer, B., Kicklighter, D., Melillo, J., Wang, C. and Zhuang, Q. (2004). Ozone effects on net primary production and carbon sequestration in the conterminous United States using a biogeochemistry model. *Tellus*, 56B, 230–248.

Feng, Z.Z., Hu, E.Z., Wang, X.K., Jiang, L.J. and Liu, X.J. (2015). Ground-level O3 pollution and its impacts on food crops in China: a review. *Environmental Pollution*, 199, 42–48.

Feng, Z.Z., Sun, J., Wan, W., Hu, E. and Calatayud, V. (2014). Evidence of widespread ozone-induced visible injury on plants in Beijing, China. *Environmental Pollution*, 193, 296–301.

Feng, Y., Ramanathan, V. and Kotamarthi, V.R. (2013). Brown carbon: a significant atmospheric absorber of solar radiation? *Atmospheric Chemistry and Physics*, 13, 8607–21.

Feng, Z.Z., Kobayashi, K., Wang, X.K. and Feng, Z.W. (2009). A meta-analysis of responses of wheat yield formation to elevated ozone concentration. *Chinese Science Bulletin*, 54(2), 249-255. doi:10.1007/s11434-008-0552-6.

Feng, Z.W., Jin, M.H., Zhang, F.Z. and Huang, Y.Z. (2003). Effects of ground-level ozone (O_3) pollution on the yields of rice and winter wheat in the Yangtze River Delta. *Journal of Environmental Sciences*, 15(3), 360–362.

Fiore, A.M., Naik, V. and Leibensperger, E.M. (2015). Air quality and climate connections. *Journal of the Air & Waste Management Association*, 65, 645–85.

Flanner, M.G., Zender, C.S., Hess, P.G., Mahowald, N.M., Painter, T.H., Ramanathan, V. and Rasch, P.J. (2009). Springtime warming and reduced snow cover from carbonaceous particles. *Atmospheric Chemistry and Physics*, 9, 2481–2497. doi:10.5194/acp-9-24812009.

Frutos, V., Gonzalez-Comadran, M., Sola, I., Jacquemin, B., Carreras, R. and Checa Vizcaino, M.A. (2015). Impact of air pollution on fertility: a systematic review. *Gynecological Endocrinology*, 31, 7–13. doi: 10.3109/09513590.2014.958992.

Fuglestvedt, J.S., Shine, K.P., Berntsen, T., Cook, J., Lee, D.S., Stenke, A., Skeie, R.B., Velders, G.J.M. and Waitz, I.A. (2010). Transport impacts on atmosphere and climate: metrics. *Atmospheric Environment*, 44, 4648–77.

Fuhrer, J. (2009). Ozone risk for crops and pastures in present and future climate. *Naturwissenschaften*, 96(2), 173–194.

Fuhrer, J. and Booker, F. (2003). Ecological issues related to ozone: agricultural issues. *Environment International*, 29(2–3), 141–54.

Fukazawa, T., Murao, N., Sato, H., Takahashi, M., Akiyama, M., Yamaguchi, T., Noguchi, I., Takahashi, H., Kozuka, C., Sakai, R., Takagi, K., Fujinuma, Y., Saigusa, N. and Matsuda, K. (2012). Deposition of aerosols on leaves in a cool-temperate larch forest in northern Hokkaido, Japan. *Asian Journal of Atmospheric Environment*, 6, 281–287.

Fuzzi, S., Baltensperger, U., Carslaw, K, Decesari, S., Denier van der Gon, H., Facchini, M.C., Fowler, D., Koren, I., Langford, B., Lohmann, U., Nemitz, E., Pandis, S., Riipinen, I., Rudich, Y., Schaap, M., Slowik, J.G., Spracklen, D.V., Vignati, E., Wild, M., Williams, M. and Gilardoni, S. (2015). Particulate matter, air quality and climate: lessons learned and future needs. *Atmospheric Chemistry and Physics*, 15, 8217–99.

Ganguly, D., Rasch, P.J., Wang, H. and Yoon, J. (2012). Fast and slow responses of the South Asian monsoon system to anthropogenic aerosols. *Geophysical Research Letters*, 39, 1–5. doi:10.1029/2012GL053043.

Gao, J.L., Yuan, Z.W., Liu, X.M., Xia, X.M., Huang, X.J. and Dong, Z.F. (2016a). Improving air pollution control policy in China – a prospective based on cost-benefit analysis. *Science of the Total Environment*, 543(A), 307–314.

Gao, S.S., Xu, P., Zhou, F. Yang, H., Zheng, C.M., Cao, W., Tao, S., Piao, S.L., Zhao, Y., Ji, X.Y., Shang, Z.Y. and Chen, M.P. (2016b). Quantifying nitrogen leaching response to fertilizer additions in China's cropland. *Environmental Pollution*, 211, 241–251. doi:10.1016/j.envpol.2016.01.010.

GBD (2018a). *Burden of disease from the joint effects of household and ambient air pollution for 2016*. Version 2. Summary of results. World Health Organization, Geneva Switzerland. http://www.who.int/airpollution/data/cities/en/.

GBD (2018b). Burden of Disease Attributable to Major Air Pollution Sources in India. GBD MAPS Working Group, G. *Health Effects Institute*, Boston, MA, USA.

GBD (2017a). *Global Burden of Disease Study 2016 (GBD 2016)*. Institute for Health Metrics and Evaluation (IHME), Seattle, WA, USA.

GBD (2017b). Global, regional, and national cancer incidence, mortality, years of life lost, years lived with disability, and disability-adjusted life-years for 32 cancer groups, 1990 to 2015: a systematic analysis for the Global Burden of Disease study. Global Burden of Disease Collaborators. *JAMA Oncology*, 3(4), 524–548.

GBD (2016). GBD MAPS Working Group. *Burden of Disease Attributable to Coal-Burning and Other Major Sources of Air Pollution in China*. Health Effects Institute, Boston, MA, USA.

GBD (2015a). *Global Burden of Disease 2013 (GBD 2013)*. Institute for Health Metrics and Evaluation (IHME), Seattle, WA, USA.

GBD (2015b). Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990-2013: a systematic analysis for the Global Burden of Disease study 2013. GBD 2015 Risk Factors Collaborators. *Lancet*, 386(10010), 2287–323.

Ghude, S.D., Bhat, G.S., Prabhakaran, T., Jenamani, R.K., Chate, D.M., Safai, P.D., Karipot, A.K., Konwar, M., Pithani, P., Sinha, V., Rao, P.S.P., Dixit, S.A., Tiwari, S., Todekar, K., Varpe, S., Srivastava, A.K., Bisht, D.S., Murugavel, P., Ali, K., Mina, U., Dharua, M., Jaya R.Y., Padmakumari, B., Hazra, A., Nigam, N., Shende, U., Lal, D.M., Chandra, B.P., Mishra, A.K., Kumar, A., Hakkim, H., Pawar, H. and Acharja, P. (2017). Winter fog experiment over the Indo-Gangetic plains of India. *Current Science*, 112(4), 767–784.

Ghude, S.D., Jena, C., Chate, D.M., Beig, G., Pfister, G.G., Kumar, R. and Ramanathan, V. (2014). Reductions in India's crop yield due to ozone. *Geophysical Research Letters*, 41, 5685–5691.

Greenbaum, D.S., Bachmann, J.D., Krewski, D., Samet, J.M., White, R. and Wyzga, R.E. (2001). Particulate air pollution standards and morbidity and mortality: case study. *American Journal of Epidemiology*, 154(12), S78–90.

Grill, D. and Golob, P. (1983). SEM-investigations of different dust depositions on the surface of coniferous needles, and the effect on the needle-wax. *Aquilo / Seria botanica*, 19, 255–261.

Gu, L.H., Baldocchi, D., Wofsy, S.C., Munger, J.W., Michalsky, J.J., Urbanski, S.P. and Boden, T.A. (2003). Response of a deciduous forest to the Mount Pinatubo eruption: enhanced photosynthesis. *Science*, 299, 2035–2038.

Gu, L., Baldocchi, D., Verma, S.B., Black, T.A., Falge, E.M. and Dowty, P.R. (2002). Advantages of diffuse radiation for terrestrial ecosystem productivity. *Journal of Geophysical Research: Atmospheres*, 107. doi.org/10.1029/2001JD001242.

Gul, C., Puppala, S.P., Kang, S., Adhikary, B., Zhang, Y., Ali, S., Li, Y. and Li, X. (2018). Concentrations and source regions of light-absorbing particles in snow/ice in northern Pakistan and their impact on snow albedo. *Atmospheric Chemistry and Physics*, 18, 4981–5000. doi.org/10.5194/acp-18-4981-2018.

Guo, X., Wang, R.Q., Chang, R.Y., Liang, X.Q., Wang, C.D., Luo, Y.J., Yuan, Y.F. and Guo, W.H. (2014). Effects of nitrogen addition on growth and photosynthetic characteristics of Acer truncatum seedlings. *Dendrobiology*, 72, 151e161.

Gupta, G.P., Kumar, B., Singh, S. and Kulshrestha, U.C. (2016). Deposition and impact of urban atmospheric dust on two medicinal plants during different seasons in NCR Delhi. *Aerosol and Air Quality Research*, 16, 2920–2932.

Gustafsson, Ö., Kruså, M., Zencak, Z., Sheesley, R.J., Granat, L., Engström, E., Praveen, P.S., Rao, P.S.P., Leck, C. and Rodhe, H. (2009). Brown clouds over South Asia: biomass or fossil fuel combustion? *Science*, 323, 495. doi:10.1126/science.1164857

Gustafsson, Ö., Kruså, M., Zencak, Z., Sheesley, R.J., Granat, L., Engström, E., Praveen, P.S., Rao, P.S.P., Leck, C. and Rodhe, H. (2009). Brown clouds over South Asia: biomass or fossil fuel combustion? *Science*, 323(5913), 495–498. doi:10.1126/science.1164857.

Habib, G., Venkataraman, C., Chiapello, I., Ramachandran, S., Boucher, O. and Shekher Reddy, M. (2006). Seasonal and interannual variability in absorbing aerosols over India derived from TOMS: relationship to regional meteorology and emissions. *Atmospheric Environment*, 40(11), 1909–1921.

Hajat, A., Hsia, C. and O'Neill, M.S. (2015). Socioeconomic disparities and air pollution exposure: a global review. *Current Environmental Health Reports*, 2(4), 440–450.

Hara, H., Kahiwakura, T., Kitayama, K., Bellingrath-Kimura, S.D., Yoshida, T., Takayanagi, M., Yamagata, S., Murao, N., Okouchi, H. and Ogata, H. (2014). Foliar rinse study of atmospheric black carbon deposition to leaves of konara oak (Quercus serrata) stands. *Atmospheric Environment*, 97, 511–518.

Hartmann, D.L., Klein Tank, A.M.G., Rusticucci, M., Alexander, L.V., Brönnimann, S., Charabi, Y., Dentener, F.J., Dlugokencky, E.J., Easterling, D.R., Kaplan, A., Soden, B.J., Thorne, P.W., Wild M. and Zhai, P.M. (2013). Observations: atmosphere and surface. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK.

Harvey, L.D.D. and Kaufmann, R.K. (2002). Simultaneously constraining climate sensitivity and aerosol radiative forcing. *Journal of Climate*, 15, 2837–61.

Heath, R.L. (2008). Modification of the biochemical pathways of plants induced by ozone: what are the varied routes of change. *Environmental Pollution*, 155, 453–463.

Heck, W.W., Taylor, O.C. and Tingey, D.T. (eds.) (1988). *Assessment of crop loss from air pollutants*. Elsevier Applied Science, London, UK.

HEI (2018). *State of Global Air / 2018: A Special Report of Global Exposure to Air Pollution and Its Disease Burden*. Health Effects Institute, Boston, MA, USA. https://www.stateofglobalair.org/sites/default/files/soga-2018-report.pdf

HEI (2010). *Outdoor Air Pollution and Health in the Developing Countries of Asia: A Comprehensive Review.* Health Effects Institute, Boston, MA, USA.

Held, I.M. and Soden, B.J. (2006). Robust responses of the hydrological cycle to global warming. *Journal of Climate*, 19, 5686–99.

Heo, J., Adams, P.J. and Gao, H.O. (2016). Public health costs of primary $PM_{2.5}$ and inorganic $PM_{2.5}$ precursor emissions in the United States. *Environment Science & Technology*, 50, 6061–70.

Heusinkveld, H.J., Wahle, T., Campbell, A., Westerink, R.H.S., Tran, L., Johnston, H., Cassee, F.R. and Schins, R.P.F. (2016). Neurodegenerative and neurological disorders by small inhaled particles. *NeuroToxicology*, 56 (Supplement C), 94–106.

Horton, D.E., Skinner, C.B., Singh, D. and Diffenbaugh, N.S. (2014). Occurrence and persistence of future atmospheric stagnation events. *Nature Climate Change*, 4, 698–703. doi.org/10.1038/nclimate2272.

Hicks, W.K., Kuylenstierna, J.C.I., Owen, A., Dentener, F., Seip, H-M. and Rodhe, H. (2008). Soil sensitivity to acidification in Asia: status and prospects. *Ambio*, 37(4), 295–303.

Hirano, T., Kiyota M. and Aiga, I. (1995). Physical effects of dust on leaf physiology of cucumber and kidney bean plants. *Environmental Pollution*, 89, 255–261.

Hopke, P.K., Cohen, D.D., Begum, B.A., Biswas, S.K., Ni, B., Pandit, G.G., Santoso, M., Chung, Y-S, Davy, P., Markwitz, A., Waheed, S., Siddique, N., Santos, F.L., Pabroa, P.C.B., Seneviratne, M.C.S, Wimolwattanapun, W., Bunprapob, S., Vuong, T.B., Duy Hien, P. and Markowicz, A. (2008). Urban air quality in the Asian region. *Science of the Total Environment*, 404(1), 103–112.

IEA (2016) *World Energy Outlook Special Report 2016 on Energy and Air Pollution.* International Energy Agency, Paris, France. www.iea.org/publications/freepublications/publicationWorldEnergyOutlookSpecialReport2016EnergyandAirPollution.pdf

IHME (2017). (IHME). GBD Compare Data Visualization. Institute for Health Metrics and Evaluation, University of Washington, Seattle, WA, USA. http://vizhub.healthdata.org/gbd-compare

Immerzeel, W.W., van Beek, L.P. and Bierkens, M.F. (2010). Climate change will affect the Asian water towers. *Science*, 328, 1382–1385.

Inada, H., Yamaguchi, M., Satoh, R., Hoshino, D., Nagasawa, A., Negishi, Y., Nouchi, I., Kobayashi, K. and Izuta, T. (2008). Effects of ozone on photosynthethic components and radical scavenging system in leaves of rice (Oryza sativa L). *Journal of Agricultural Meteorology*, 64, 243–255. doi:10.2480/agrmet.64.4.10.

IPCC (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J. ,Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, UK.

IPCC (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds.)]. Cambridge University Press, Cambridge, UK.

Isaksen, I.S.A., Granier, C., Myhre, G., Berntsen, T.K., Dalsøren, S.B., Gauss, M., Klimont, Z., Benestad, R., Bousquet, P., Collins, W., Cox, T., Eyring, V., Fowler, D., Fuzzi, S., Jöckel, P., Laj, P., Lohmann, U., Maione, M., Monks, P., Prevot, A.S.H., Raes, F., Richter, A., Rognerud, B., Schulz, M., Shindell, D., Stevenson, D.S., Storelvmo, T., Wang, W.C., van Weele, M., Wild, M. and Wuebbles, D. (2009). Atmospheric composition change: climate–chemistry interactions. *Atmospheric Environment*, 43, 5138–92.

Ishii, S., Marshall, F.M., Bell, J.N.B. and Abdullah, A.M. (2004). Impact of ambient air pollution on locally grown rice cultivars (*Oryza sativa L.*) in Malaysia. *Water, Air, & Soil Pollution*, 154, 187–201. doi:10.1023/B:WATE.0000022964.55434.05.

Izuta, T. (2017). *Air Pollution Impacts on Plants in East Asia*. Springer Nature, Tokyo, Japan. doi:10.1007/978-4-431-56438-6.

Izuta, T., Yamaguchi, M., Yamane, K., Nakaba, S., Ishida, A., Yazaki, K., Noguchi, K. and Lenggoro, I.W. (2014). Experimental studies on the effects of black carbon particles on forest tree species. *Earozoru Kenkyu*, 29, 148–159 (in Japanese with English summary).

Jacob, D.J. and Winner, D.A. (2009). Effect of climate change on air quality. *Atmospheric Environment*, 43, 51–63.

Jäger, H.J., Unsworth, M., De Temmermann, L. and Mathy, P. (eds.) (1992). *Effects of Air Pollution on Agricultural Crops in Europe – Results of the European Open-Top Chamber Project*. Air Pollution Research Report 46. Commission of the European Communities, Brussels, Belgium.

Jain, S.K. (2008). Impact of retreat of Gangotri glacier on the flow of Ganga River. *Current Science*, 95, 1012–4.

Jin, M., Feng, Z. and Zhang, F. (2001). Impacts of ozone on the biomass and yield of rice in open-top chamber. *Journal of Environmental Science* (China), 13, 233–236.

Johansson, D. (2012). Economics- and physical-based metrics for comparing greenhouse gases. *Climatic Change*, 110, 123–41.

Jones, L., Provins, A., Holland, M., Mills, G., Hayes, F., Emmett, B., Hall, J., Sheppard, L., Smith, R., Sutton, M., Hicks, K., Ashmore, M., Haines-Young, R. and Harper-Simmonds, L. (2014). A review and application of the evidence for nitrogen impacts on ecosystem services. *Ecosystem Services*, 7, 76–88. 10.1016/j.ecoser.2013.09.001.

Joos, F., Roth, R., Fuglestvedt, J.S., Peters, G.P., Enting, I.G., von Bloh, W., Brovkin, V., Burke, E.J., Eby, M., Edwards, N.R., Friedrich, T., Frölicher, T.L., Halloran, P.R., Holden, P.B., Jones, C., Kleinen, T., Mackenzie, F.T., Matsumoto, K., Meinshausen, M., Plattner, G.-K., Reisinger, A., Segschneider, J., Shaffer, G., Steinacher, M., Strassmann, K., Tanaka, K., Timmermann, A. and Weaver, A.J. (2013). Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmospheric Chemistry and Physics*, 13, 2793–825.

Kan, H., London, S.J., Chen, G., Zhang, Y., Song, G., Zhao, N., Jiang, L. and Chen, B. (2008). Season, sex, age, and education as modifiers of the effects of outdoor air pollution on daily mortality in Shanghai, China: the Public Health and Air Pollution in Asia (PAPA) study. *Environmental Health Perspectives*, 116(9), 1183–1188.

Kanniah, K.D., Beringer, J., North, P.R. and Hutley, L. (2012). Control of atmospheric particles on diffuse radiation and terrestrial plant productivity. *Progress in Physical Geography*, 36, 209–237.

Khokhar, M.F., Yasmin, N., Fatima, N., Beirle, S. and Wagner, T. (2015). Detection of trends and seasonal variation in tropospheric nitrogen dioxide over Pakistan. *Aerosol and Air Quality Research*, 15, 2508–2524. doi:10.4209/aaqr.2015.03.0157.

Kim Oanh, N.T., Upadhyay, N., Zhuang, Y.H., Hao, Z.P., Murthy, D.V.S. and Lestari, P. (2006). Particulate air pollution in six Asian cities: spatial and temporal distributions and associated sources. *Atmospheric Environment*, 40, 3367–3380.

Kioumourtzoglou, M.A., Schwartz, J.D., Weisskopf, M.G., Melly, S.J., Wang, Y., Dominici, F. and Zanobetti, A. (2016). Long-term $PM_{2.5}$ exposure and neurological hospital admissions in the northeastern United States. *Environmental Health Perspectives*, 124(1), 23–29.

Knohl, A. and Baldocchi, D.D. (2008). Effects of diffuse radiation on canopy gas exchange processes in a forest ecosystem. *Journal of Geophysical Research: Biogeosciences*, 113.

Knutti, R. (2008). Why are climate models reproducing the observed global surface warming so well? *Geophysical Research Letters*, 35. doi.org/10.1029/2008GL034932.

Kobayashi, K. (2015). FACE-ing the challenges of increasing surface ozone concentration in Asia. *Journal of Agricultural Meteorology*, 71(3), 161–166.

Kobayashi, K., Okada, M. and Nouchi, I. (1995). Effects of ozone on dry matter partitioning and yield of Japanese cultivars of rice (Oryza sativa L.). *Agriculture Ecosystems & Environment*, 53, 109–122. doi:10.1016/0167– 8809(94)00564-U.

Kodros, J.K., Wiedinmyer, C., Ford, B., Cucinotta, R., Gan, R., Magzamen, S. and Pierce, J.R. (2016). Global burden of mortalities due to chronic exposure to ambient $PM_{2.5}$ from open combustion of domestic waste. *Environmental Research Letters*, 11, 124022.

Kohno, Y., Matsumura, H., Ishii, T. and Izuta, T. (2005) Establishing critical levels of air pollutants for protecting East Asian vegetation – a challenge. In: *Plant Responses to Air Pollution and Global Change* [Omasa, K., Nouchi, I., De Kok, L.J. (eds.)]. Springer, Tokyo.

Koplitz, S.N., Mickley, L.J., Marlier, M.E., Buonocore, J.L., Kim, P.S., Liu, T., Sulprizio, M.O., DeFries, R.S., Jacob, D.J. and Schwartz, L. (2016). Public health impacts of the severe haze in Equatorial Asia in September–October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure. *Environmental Research Letters*, 11, 094023. doi:10.1088/1748-9326/11/9/094023.

Krewski, D., Jerrett, M., Burnett, R.T., Ma, R., Hughes, E., Shi, Y., Turner, M.C., Pope, C.A. III., Thurston, G., Calle, E.E. and Thun, M.J., with Beckerman, B., DeLuca, P., Finkelstein, N., Ito, K., More, D.K., Newbold, K.B., Ramsay, T., Ross, Z., Shin, H. and Tempalski, B. (2009). *Extended Follow-up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality*. Health Effects Institute, Boston, MA, USA.

Kulkarni, A.V., Bahuguna, I.M., Rathore, B.P., Singh, S.K., Randhawa, S.S., Sood, R.K. and Dhar. S. (2007). Glacial retreat in Himalaya using Indian remote sensing satellite data. *Current Science*, 92, 69–74.

Kulshrestha, U. (2013). Acid rain. In: *Encyclopedia of Environmental Management* [Jorgensen, S.E. (ed.)]. Vol. I, 8–22. Taylor & Francis, Abingdon, UK.

Kumar, R., Sharma, S.K., Thakur, J.S., Lakshmi, P.V., Sharma, M.K. and Singh, T. (2010). Association of air pollution and mortality in the Ludhiana city of India: a time-series study. *Indian Journal of Public Health*, 54(2), 98–103.

LaDochy, S and Witiw, M.R. (2013). Fog hazard mitigation. In: *Encyclopedia of Natural Hazards* [Bobrowsky, P.T. (ed.)]. pp. 338–342. Springer, Berlin, Germany.

Lal, S., Venkataramani, S., Naja, M., Kuniyal, J.C., Mandal, T.K., Bhuyan, P.K., Kumari, K.M., Tripathi, S.M., Sarkar, U., Das, T., Swamy, Y.V., Gopal, K.R., Gadhavi, H. and Kumar, M.K.S. (2017). Loss of crop yields in India due to surface ozone: an estimation based on a network of observations. *Environmental Science and Pollution Research*, 24(26), 20972–20981. doi:10.1007/s11356-017-9729-3.

Landrigan, P.J., Fuller, R., Acosta, N.J.R., Adeyi, O., Arnold, R., Basu, N., Baldé, A.B., Bertollini, R., Bose-O'Reilly, S., Boufford, J.I., Breysse, P.N., Chiles, T., Mahidol, C., Coll-Seck, A.M., Cropper, M.L., Fobil, J., Fuster, V., Greenstone, M., Haines, A., Hanrahan, D., Hunter, D., Khare, M., Krupnick, A., Lanphear, B., Lohani, B., Martin, K., Mathiasen, K.V., McTeer, M.A., Murray, C.J.L., Ndahimananjara, J.D., Perera, F., Potočnik, J., Preker, A.S., Ramesh, J., Rockström, J., Salinas, C., Samson, L.D., Sandilya, K., Sly, P.D., Smith, K.R., Steiner, A., Stewart, R.B., Suk, W.A., van Schayck, O.C.P., Yadama, G.N., Yumkella, K. and Zhong, M. (2017). The Lancet Commission on pollution and health. *Lancet*, 391, 10119.

Lashof, D.A. and Ahuja, D.R. (1990). Relative contributions of greenhouse gas emissions to global warming. *Nature*, 344, 529–31.

Laskin, A., Laskin, J. and Nizkorodov, S.A. (2015). Chemistry of atmospheric brown carbon. *Chemical Reviews*, 115, 4335–82.

Lau, K-M. and Kim, K-M. (2006). Observational relationships between aerosol and Asian monsoon rainfall, and circulation. *Geophysical Research Letters*, 33(L21810). doi:10.1029/2006GL027546.

Le Blanc, D. (2015). *Towards Integration at Last? The Sustainable Development Goals as a Network of Targets*. UN DESA Working Paper 23 (141). UN Department of Economic and Social Affairs, New York, NY, USA.http://www.un.org/esa/desa/papers/2015/wp141_2015.pdf

Lee, C.C. and Shibao, P. (2016). Fighting fires and haze in Indonesia. *The Jakarta Post*. www.thejakartapost.com/academia/2016/09/06/fighting-fires-and-haze-in-indonesia.html

Lee, J.-B., Cha, J., Hong, S., Choi, J., Myoung, J., Park, R.J., Woo, J., Ho, C., Han, J. and Song, C. (2015). Projections of summertime ozone concentration over East Asia under multiple IPCC SRES emission scenarios. *Atmospheric Environment*, 106, 335–346. doi.org/10.1016/j.atmosenv.2015.02.019.

Levasseur, A., Cavalett, O., Fuglestvedt, J.S., Gasser, T., Johansson, D.J.A., Jørgensen, S.V., Raugei, M., Reisinger, A., Schivley, G., Strømman, A., Tanaka, K. and Cherubini, F. (2016a). Enhancing life cycle impact assessment from climate science: review of recent findings and recommendations for application to LCA. *Ecological Indicators*, 71, 163–74.

Levasseur, A., de Schryver, A., Hauschild, M., Kabe, Y., Sahnoune, A., Tanaka, K. and Cherubini, F. (2016b). Greenhouse gas emissions and climate change impacts. In: *Global Guidance for Life Cycle Impact Assessment Indicators,* Vol.1 [Frischknecht, R. and Jolliet, O. (eds.)]. pp 59–75.United Nations Environment Programme, Paris, France.

Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D. and Pozzer, A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature*, 525, 367–371. doi:10.1038/nature15371.

Levy, R.J. (2015). Carbon monoxide pollution and neurodevelopment: A public health concern. *Neurotoxicology and Teratology*, 49, 31–40. doi:10.1016/j.ntt.2015.03.001.

Li, C., Bosch, C., Kang, S., Andersson, A., Chen, P., Zhang, Q., Cong, Z., Chen, B., Qin, D. and Gustafsson, Ö. (2016). Sources of black carbon to the Himalayan–Tibetan Plateau glaciers. *Nature Communications*, 7. doi:10.1038/ncomms12574.

Lippmann, M. (2013). Exposure science in the 21st century: a vision and a strategy. *Journal of Exposure Science and Environmental Epidemiology* 23(1), 1.

Lippmann, M., Chen, L.C., Gordon, T., Ito, K. and Thurston, G.D. (2013). National Particle Component Toxicity (NPACT) Initiative: integrated epidemiologic and toxicologic studies of the health effects of particulate matter components. *Research Report (Health Effects Institute)*, 177, 5–13.

Liu, H., Fu, M., Jin, X., Shang, Y., Shindell, D., Shindell, C. and He, K. (2016). Health and climate impacts of ocean-going vessels in East Asia. *Nature Climate Change*, 6, 1037–1041.

Loomis, D., Grosse, Y., Lauby-Secretan, B., El Ghissassi, F., Bouvard, V., Benbrahim-Tallas, L., Guha, N., Baan, R., Mattock, H. and Straif, K. (2013). The carcinogenicity of outdoor air pollution. *Lancet Oncology*, 14(13), 1262–3.

Lu, Z., Streets, D.G., Zhang, Q., and Wang, S. (2012). A novel back-trajectory analysis of the origin of black carbon transported to the Himalayas and Tibetan Plateau during 1996–2010. *Geophys. Res. Lett.*, 39, L01809. doi:10.1029/2011GL049903.

Lu, X.K., Mo, J.M., Gilliam, F.S., Yu, G.R., Zhang, W., Fang, Y.T. and Huang, J. (2011). Effects of experimental nitrogen additions on plant diversity in tropical forests of contrasting disturbance regimes in southern China. *Environmental Pollution*, 159, 2228e2235.

Lu, X.K., Mo, J.M., Gilliam, F.S., Zhou, G.Y. and Fang, Y.T. (2010). Effects of experimental nitrogen additions on plant diversity in an old-growth tropical forest. *Global Change Biology*, 16, 2688e2700.

Lu, X.K., Mo, J.M., Gundersern, P., Zhu, W.X., Zhou, G.Y., Li, D.J. and Zhang, X., (2009). Effect of simulated N deposition on soil exchangeable cations in three forest types of subtropical China. *Pedosphere*, 19, 189e198.

Lu, X.K., Mo, J.M. and Dong, S. (2008). Effects of nitrogen deposition on forest biodiversity: a review. *Acta Ecologica Sinica*, 28, 5532e5548 (in Chinese).

Lund, M.T., Berntsen, T., Fuglestvedt, J.S., Ponater, M. and Shine, K.P. (2012). How much information is lost by using global-mean climate metrics? An example using the transport sector. *Climatic Change*, 113, 949–63.

Luo, C., Zhu, X., Yao, C., Hou, L., Zhang, J., Cao, J. and Wang, A. (2015). Short-term exposure to particulate air pollution and risk of myocardial infarction: a systematic review and meta-analysis. *Environmental Science and Pollution Research*, 22(19), 14651–14662. doi:10.1007/s11356-015-5188-x.

Luo, K., Jhu, J., Liu, G., Tang, H., Chunhua, L. and Zeng, Q. (2013). Responses of dry matter production and distribution in rice (Oryza sativa L.) to ozone and high nitrogen supply. *Chinese Journal of Applied Ecology*, 19(2), 286–292 (in Chinese).

Ma, G. (1991). Nutritional distributions and declining armand pine in southwestern China. *Water, Air, and Soil Pollution*, 54, 91–96.

Mahowald, N. (2011). Aerosol indirect effect on biogeochemical cycles and climate. *Science*, 334, 794–6.

Maione, M., Fowler, D., Monks, P.S., Reis, S., Rudich, Y., Williams, M.L. and Fuzzi, S. (2016). Air quality and climate change: designing new win-win policies for Europe. E*nvironmental Science & Policy*, 65, 48–57.

Malley, C.S., Kuylenstierna, J.C.I., Vallack, H.W., Henze, D.K., Blencowe, H. and Ashmore, M.R. (2017). Preterm birth associated with maternal fine particulate matter exposure: a global, regional and national assessment. *Environment International,* 101 (Supplement C), 173–182.

Manne, A.S. and Richels, R.G. (2001). An alternative approach to establishing trade-offs among greenhouse gases. *Nature*, 410, 675–7.

Massman, W.J. (2004). Toward an ozone standard to protect vegetation based on effective dose: a review of deposition resistances and a possible metric. *Atmospheric Environment*, 38, 2323–2337.

Martin, M.J., Host, G.E. and Lenz, K.E. (2001). Stimulating the growth response of aspen to elevated ozone: a mechanistic approach to scaling a leaf-level model of ozone effects on photosynthesis to a complex canopy architecture. *Environmental Pollution*, 115, 425–436.

Martin, M.J., Farage, P.K., Humphries, S.W., Long, S.P. (2000). Can the stomatal changes caused by acute ozone exposure be predicted by changes occurring in the mesophyll? A simplification for models of vegetation response to the global increase in tropospheric elevated ozone episodes. *Australian Journal of Plant Physiology,* 27, 211–219.

Matinga, M.N. (2010). "We grow up with it": an ethnographic study of the experiences, perceptions and responses to the health impacts of energy acquisition and use in rural South Africa. University of Twente, Enschede. doi:10.3990/1.9789036530965.

Melamed, M.L., Schmale, J. and von Schneidemesser, E. (2016). Sustainable policy – key considerations for air quality and climate change. *Current Opinion in Environmental Sustainability*, 23, 85–91.

Menon, S., Koch, D., Beig, G., Sahu, S., Fasullo, J. and Orlikowski, D. (2010). Black carbon aerosols and the third polar ice cap. *Atmospheric Chemistry and Physics*, 10, 4559–4571.

Menon, S., Hansen, J. and Nazarenko, L.L.Y. (2002). Climate effects of black carbon aerosols in China and India. *Science*, 297(5590), 2250–2253. doi:10.1126/science.1075159.

Meo, S.A., Memon, A.N., Sheikh, S.A., Rouq, F.A., Mahmood Usmani, A., Hassan, A. and Arain, S.A. (2015). Effect of environmental air pollution on type 2 diabetes mellitus. *European Review for Medical and Pharmacological Sciences*, 19(1), 123–128.

Mercado, L.M., Bellouin, N., Sitch, S., Boucher, O., Huntingford, C., Wild, M. and Cox, P.M. (2009). Impact of changes in diffuse radiation on the global land carbon sink. *Nature*, 458(7241), 1014–1017. doi: 10.1038/nature07949.

Middleton, N. and Kang, U. (2017). Sand and dust storms: impact mitigation. *Sustainability* 2017, 9(6), 1053. doi:10.3390/su9061053.

Mills, G., Wagg, S. and Harmens, H. (2013). *Ozone Pollution: Impacts On Ecosystem Services and Biodiversity*. ICP Vegetation Programme Coordination Centre, Centre for Ecology and Hydrology, Bangor, UK.

Mills, G., Buse, A., Gimeno, B., Bermejo, V., Holland, M., Emberson, L. and Pleijel, H. (2007). A synthesis of AOT40-based response functions and critical levels of ozone for agricultural and horticultural crops. *Atmospheric Environment*, 41, 2630–2643.

Min, Q.L. (2005). Impacts of aerosols and clouds on forest-atmosphere carbon exchange. *Journal of Geophysical Research: Atmospheres*, 110.

Ming, Y., Ramaswamy, V. and Persad, G. (2010). Two opposing effects of absorbing aerosols on global-mean precipitation. *Geophysical Research Letters*, 37(L13701).

Mishra, V. (2001). Gender aspects of indoor air pollution and health: an analysis of gender differentials in the effect of cooking smoke on acute respiratory infections in children. World Health Organization. www.who.int/gender/documents/Vmishra.pdf

Mishra, A.K. and Agrawal, S.B. (2015). Biochemical and physiological characteristics of tropical mung bean (Vigna radiata L.) cultivars against chronic ozone stress: an insight to cultivar-specific response. *Protoplasma*, 252, 797–811.

Mishra, M. and Kulshrestha, U. (2017). Chemical characteristics and deposition fluxes of dust-carbon mixed coarse aerosols at three sites of Delhi, NCR. *Journal of Atmospheric Chemistry*, 74(4), 399–421.

Mo, J.M., Li, D.J. and Gundersen, P. (2008). Seedling growth response of two tropical tree species to nitrogen deposition in southern China. *European Journal of Forest Research*, 127, 275e283.

Mohan, M. and Payra, S. (2009). Influence of aerosol spectrum and air pollutants on fog formation in urban environment of megacity Delhi, India. *Environmental Monitoring and Assessment*, 151(1), 265–277.

Monks, P.S., Archibald, A.T., Colette, A., Cooper, O., Coyle, M., Derwent, R., Fowler, D., Granier, C., Law, K.S., Mills, G.E., Stevenson, D.S., Tarasova, O., Thouret, V., von Schneidemesser, E., Sommariva, R., Wild, O. and Williams, M.L. (2015). Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer. *Atmospheric Chemistry and Physics*, 15, 8889–973.

Myhre, G., Samset, B.H., Schulz, M., Balkanski, Y., Bauer, S., Berntsen, T.K., Bian, H., Bellouin, N., Chin, M., Diehl, T., Easter, R.C., Feichter, J., Ghan, S.J., Hauglustaine, D., Iversen, T., Kinne, S., Kirkevåg, A., Lamarque, J.F., Lin, G., Liu, X., Lund, M.T., Luo, G., Ma, X., van Noije, T., Penner, J.E., Rasch, P.J., Ruiz, A., Seland, Ø., Skeie, R.B., Stier, P., Takemura, T., Tsigaridis, K., Wang, P., Wang, Z., Xu, L., Yu, H., Yu, F., Yoon, J.H., Zhang, K., Zhang, H. and Zhou, C. (2013a). Radiative forcing of the direct aerosol effect from AeroCom Phase II simulations. *Atmospheric Chemistry and Physics*, 13, 1853–77.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T. and Zhang, H. (2013b). Anthropogenic and natural radiative forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y.. Bex. V. and Midgley, P.M. (eds.)], pp. 659–740. Cambridge University Press, Cambridge, UK. doi:10.1017/CBO9781107415324.018.

Nakahara, O., Takahashi, M., Sase, H., Yamada, T., Matsuda, K., Ohizumi, T., Fukuhara, H., Inoue, T., Takahashi, A., Kobayashi, H., Hatano, R. and Hakamata, T. (2010). Soil and stream water acidification in a forested catchment in central Japan. *Biogeochemistry*, 97, 141–158.

Nghiem, L.H. (2007). *Photochemical Smog Modelling for Prediction of Ground-level Ozone Over the Continental Southeast Asia Region to Assess Impacts on Rice Crop Yield*. Dissertation. Asian Institute of Technology (AIT), Pathumthani, Thailand.

Nghiem, L.H and Kim Oanh, N.T. (2009). Comparative analysis of maximum daily ozone levels in urban areas predicted by different statistical models. *ScienceAsia*, 35, 276–283. doi:10.2306 scienceasia1513-1874.2009.35.276.

Nghiem, L.H and Kim Oanh, N.T. (2008). Evaluation of the Mesoscale Meteorological Model (MM5)-Community Multi-Scale Air Quality Model (CMAQ) performance in hindcast and forecast of ground-level ozone. *Journal of the Air & Waste Management Association*, 58(10), 1341–1350.

Nishiwaki, Y., Michikawa, T., Takebayashi, T., Nitta, H., Iso, H., Inoue, M. and Tsugane, S. (2013). Long-term exposure to particulate matter in relation to mortality and incidence of cardiovascular disease: the JPHC Study. *Journal of Atherosclerosis and Thrombosis*, 20(3), 296–309.

Niu, F., Li, Z., Li, C., Lee, K.H. and Wang, M. (2010). Increase of wintertime fog in China: potential impacts of weakening of the Eastern Asian monsoon circulation and increasing aerosol loading. *Journal of Geophysical Research*, 115, 1–12. doi:10.1029/2009JD013484.

Northcross, A.L., Hwang, N., Balakrishnan, K. and Mehta, S. (2015). Assessing exposures to household air pollution in public health research and program evaluation. *Ecohealth*, 12 (1), 57–67.

Ocko, I.B., Hamburg, S.P., Jacob, D.J., Keith, D.W., Keohane, N.O., Oppenheimer, M., Roy-Mayhew, J.D., Schrag, D.P. and Pacala, S.W. (2017). Unmask temporal trade-offs in climate policy debates. *Science*, 356, 492–3.

OECD (2016). *The Economic Consequences of Outdoor Air Pollution*. Organisation for Economic Co-operation and Development, Paris, France.

OECD (2014). *The Cost of Air Pollution-Policy Highlights: Health Impacts of Road Transport*. Organisation for Economic Co-operation and Development, Paris, France.

Oliphant, A.J., Dragoni, D., Deng, B., Grimmond, C.S.B., Schmid, H.P. and Scott, S.L. (2011). The role of sky conditions on gross primary production in a mixed deciduous forest. *Agricultural and Forest Meteorology*, 151, 781–791.

Ollinger, S.V., Aber, J.D. and Reich, P.B. (1997). Simulating ozone effects on forest productivity: interactions among leaf-, canopy-, and stand-level processes. *Ecological Applications*, 7(4), 1237–1251.

O'Neill, B.C. (2003). Economics, natural science, and the costs of global warming potentials. *Climatic Change*, 58, 251–60.

Oskin, B. (2014). Air pollution intensifies Pacific storms. Scientific American, 15 April 2014. www.scientificamerican.com/article/air-pollution-intensifies-pacific-storms/

Otero, N., Sillmann, J., Schnell, J.L., Rust, H.W. and Butler, T. (2016). Synoptic and meteorological drivers of extreme ozone concentrations over Europe. *Environmental Research Letters*, 11, 2.

Painter, T., Deems, J., Belnap, J., Hamlet, A., Landry, C. and Udall, B. (2010). Response of Colorado River runoff to dust radiative forcing in snow. *Proceedings of the National Academy of Sciences of the United States of America*, 107, 17125–17130. doi.org/10.1073/pnas.0913139107.

Payra, S. and Mohan, M. (2014). Multirule based diagnostic approach for the fog predictions using WRF modelling tool. *Advances in Meteorology*, 456065. doi.org/10.1155/2014/456065.

Perera, F.P. (2017). Multiple threats to child health from fossil fuel combustion: impacts of air pollution and climate change. *Environmental Health Perspectives*, 125(2), 141–148.

Perera, F.P., Chang, H-W., Tang, D., Roen, E.L., Herbstman, J., Margolis, A., Huang, T-J., Miller, R.L., Wang, S. and Rauh, V. (2014). Early-life exposure to polycyclic aromatic hydrocarbons and ADHD behavior problems. *PLOS ONE*, 9(11), e111670.

Permadi, D.A. and Kim Oanh, N.T. (2008). Episodic ozone air quality in Jakarta in relation to meteorological conditions. *Atmospheric Environment*, 41(28), 6806–6815.

Pinder, R.W., Adams, P.J. and Pandis, S.N. (2007). Ammonia emission controls as a cost-effective strategy for reducing atmospheric particulate matter in the Eastern United States. *Environmental Science and Technology*, 41, 380–6.

Pope, C.A. III and Dockery, D.W. (2006). Health effects of fine particulate air pollution: lines that connect. *Journal of the Air & Waste Management Association*, 56(6), 709–42. Published online 29 Feb 2012: doi:10.1080/10473289.2006.10464485.

Pope, C.A. III, Renlund, D.G., Kfoury, A.G., May, H.T. and Horne, B.D. (2008). Relation of heart failure hospitalization to exposure to fine particulate air pollution. *American Journal of Cardiology*, 102(9), 1230–4.

Praveen, P.S., Ahmed, T., Kar, A., Rehman, I.H. and Ramanathan, V. (2012). Link between local scale BC emissions in the Indo-Gangetic Plains and large scale atmospheric solar absorption. *Atmospheric Chemistry and Physics*, 12, 1173–1187. doi.org/10.5194/acp-12-1173-2012.

Qian, Y., Yasunari, T.J., Doherty, S.J., Flanner, M.G., Lau, W.K., Ming, J., Wang, H., Wang, M., Warren, S.G. and Zhang, R. (2015). Light-absorbing particles in snow and ice: measurement and modeling of climatic and hydrological impact. *Advances in Atmospheric Sciences*, 32, 64–91. doi.org/10.1007/s00376-014-0010-0.

Qian, Y., Zhu, M., Cai, B., Yang, Q., Kan, H., Song, G., Jin, W., Han, M. and Wang, C. (2013). Epidemiological evidence on association between ambient air pollution and stroke mortality. *Journal of Epidemiology and Community Health*, 67(8), 635–640.

Qian, Y., Flanner, M.G., Leung, L.R. and Wang, W. (2011). Sensitivity studies on the impacts of Tibetan Plateau snowpack pollution on the Asian hydrological cycle and monsoon climate. *Atmospheric Chemistry and Physics*, 11, 1929–1948.

Qu, B., Ming, J., Kang, S.C., Zhang, G.S., Li, Y.W., Li, C.D., Zhao, S.Y., Ji, Z.M. and Cao, J.J. (2014). The decreasing albedo of the Zhadang glacier on western Nyainqentanglha and the role of light-absorbing impurities. *Atmospheric Chemistry and Physics*, 14(20), 11117–11128. doi:10.5194/acp-14-11117.

Rai, R., Singh, A.A., Agrawal, S.B. and Agrawal, M. (2016). Tropospheric O3: a cause of concern for terrestrial plants. In: *Plant Responses to Air Pollution* [Kulshrestha, U. and Saxena, P. (eds.)] pp. 165–195. Springer, Berlin, Germany.

Rai, R., Agrawal, M. and Agrawal, S.B. (2010). Threat to food security under current levels of ground level ozone: a case study for Indian cultivars of rice. *Atmospheric Environment*, 44, 4272–4282.

Rai, R., Agrawal, M. and Agrawal, S.B. (2007). Assessment of yield losses in tropical wheat using open top chambers. Atmospheric Environment, 41, 9543–9554.

Raina, V.K. and Sangewar, C. (2007). Siachen glacier of Karakorum Mountains, Ladakh: its secular retreat. Journal of the Geological Society of India, 70, 11–6.

Rajarathnam, U., Sehgai, M., Nairy, S., Patnayak, R.C., Chhabra, S.K., Kilnani and Ragavan, K.V. (2011). Part 2. Time-series study on air pollution and mortality in Delhi. Research Report (Health Effects Institute), 157, 47–74.

Ram, K., Sarin, M.M. and Tripathi, S.N. (2011).Temporal trends in atmospheric $PM_{2.5}$, PM_{10}, elemental carbon, organic carbon, water-soluble organic carbon, and optical properties: impact of biomass burning emissions in the Indo-Gangetic Plain, *Environmental Science and Technology*, 2, 686–695.

Ramanathan, V. (2006). Atmospheric brown clouds; health, climate and agriculture. Interactions between Global Change and Human Health, Pontifical Academy of Sciences, *Scripta Varia*, 106. http://www.pas.va/content/dam/accademia/pdf/sv106/sv106-ramanathan.pdf

Ramanathan, V. and Carmichael, G. (2008). Global and regional climate changes due to black carbon. *Nature Geoscience*, 1(4), 221–227.

Ramanathan, V. and Feng, Y. (2009). Air pollution, greenhouse gases and climate change: global and regional perspectives. *Atmospheric Environment*, 43, 37–50. doi:10.1016/j.atmosenv.2008.09.063.

Ramanathan, V. and Xu, Y. (2010). The Copenhagen Accord for limiting global warming: criteria, constraints, and available avenues. *Proceedings of the National Academy of Sciences of the United States of America*, 107, 8055–62.

Ramanathan, V., Ramana, M.V., Roberts, G., Kim, D., Corrigan, C., Chung, C. and Winker, D. (2007). Warming trends in Asia amplified by brown cloud solar absorption. *Nature*, 448, 575–578.

Ramanathan, V., Crutzen, P.J., Lelieveld, J., Mitra, A.P., Althausen, D., Anderson, J., Andreae, M.O., Cantrell, W., Cass, G.R., Chung, C.E., Clarke, A.D., Coakley, J.A., Collins, W.D., Conant, W.C., Dulac, F., Heintzenberg, J., Heymsfield, A.J., Holben, B., Howell, S., Hudson, J., Jayaraman, A., Kiehl, J.T., Krishnamurti, T.N., Lubin, D., McFarquhar, G., Novakov, T., Ogren, J.A., Podgorny, I.A., Prather, K., Priestley, K., Prospero, J.M., Quinn, P.K., Rajeev, K., Rasch, P., Rupert, S., Sadourny, R., Satheesh, S.K., Shaw, G.E., Sheridan, P. and Valero, F.P.J. (2001). Indian Ocean Experiment: an integrated analysis of the climate forcing and effects of the great Indo-Asian haze. *Journal of Geophysical Research: Atmospheres*, 106, 28371–28398. doi.org/10.1029/2001JD900133.

Reich, P.B. (1987). Quantifying plant response to ozone: a unifying theory. *Tree Physiology*, 3, 63–91.

Ren, W., Tian, H.Q., Liu, M.L., Zhang, C., Chen, G.S., Pan, S.F., Felzer, B. and Xu, X.F. (2007). Effects of tropospheric ozone pollution on net primary productivity and carbon storage in terrestrial ecosystems of China. *Journal of Geophysical Research: Atmospheres*, 112, 1984–2012.

Roderick, M.L., Farquhar, G.D., Berry, S.L. and Noble, I.R. (2001). On the direct effect of clouds and atmospheric particles on the productivity and structure of vegetation. *Oecologia*, 129, 21–30.

Royal Society (2008). *Ground-level Ozone in the 21st Century: Future Trends, Impacts and Policy Implications*. The Royal Society, London, UK. https://royalsociety.org/~/media/Royal_Society_Content/policy/publications/2008/7925.pdf

Samet, J.M., Dominici, F., Zeger, S.L., Schwartz, J. and Dockery, D.W. (2000). The National Morbidity, Mortality, and Air Pollution Study. Part I: Methods and Methodologic Issues. *Research Report (Health Effects Institute)*, 94(1), 5–14.

Samoli, E., Peng, R., Ramsay, T., Pipkou, M., Touloumi, G., Dominici, F., Burnett, R., Cohen, A., Krewski, D., Samet, J. and Katsouyanni, K. (2008). Acute effects of ambient particulate matter on mortality in Europe and North America: results from the APHENA study. *Environmental Health Perspectives*, 116(11), 1480–6.

Samset, B.H., Myhre, G., Forster, P.M., Hodnebrog, Ø., Andrews, T., Boucher, O., Faluvegi, G., Fläschner, D., Kasoar, M., Kharin, V., Kirkevåg, A., Lamarque, J.F., Olivié, D., Richardson, T.B., Shindell, D., Takemura, T. and Voulgarakis, A. (2018). Weak hydrological sensitivity to temperature change over land, independent of climate forcing. *npj Climate and Atmospheric Science*, 1(1), 3. doi:10.1038/s41612-017-0005-5.

Samset, B.H., Myhre, G., Forster, P.M., Hodnebrog, Ø., Andrews, T., Faluvegi, G., Fläschner, D., Kasoar, M., Kharin, V., Kirkevåg, A., Lamarque, J.F., Olivié, D., Richardson, T., Shindell, D., Shine, K.P., Takemura, T. and Voulgarakis, A. (2016). Fast and slow precipitation responses to individual climate forcers: a PDRMIP multimodel study. *Geophysical Research Letters*, 43(6), 2782–2791. doi:10.1002/2016GL068064.

Sanderson, M.G., Collins, W.J., Hemming, D.L. and Betts, R.A. (2007). Stomatal conductance changes due to increasing carbon dioxide levels: Projected impact on surface ozone levels. *Tellus*, 59B, 404–411.

Sarkar, A. and Agrawal, S.B. (2012). Evaluating the response of two high yielding Indian rice cultivars against ambient and elevated levels of ozone by using open top chambers. *Journal of Environmental Management*, 95, S19–S24.

Sarkar, A. and Agrawal, S.B. (2010). Elevated ozone and two modern wheat cultivars: an assessment of dose dependent sensitivity with respect to growth, reproductive and yield parameters. *Environmental and Experimental Botany*, 69, 328–337.

Sarkar, C., Kumar, V. and Sinha, V. (2013). Massive emissions of carcinogenic benzenoids from paddy residue burning in North India. *Current Science,* 104(12), 1703–1709.

Sase, H., Takamatsu, T., Yoshida, T. and Inubushi, K. (1998). Changes in properties of epicuticular wax and the related water loss in Japanese cedar (Cryptomeria japonica) affected by anthropogenic environmental factors. *Canadian Journal of Forest Research*, 28, 546–556.

Schmale, J., Shindell, D., von Schneidemesser, E., Chabay, I. and Lawrence, M. (2014). Air pollution: clean up our skies. *Nature*, 515, 335–7.

Seinfeld, J.H. and Pandis, S.N. (2016). *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change*. 3rd edition. Wiley, Hoboken, NJ, USA.

Shah, P.S. and Balkhair, T. (2011). Air pollution and birth outcomes: a systematic review. *Environment International*, 37, 498-516. doi:10.1016/j.envint.2010.10.009.

Shah, A.S.V., Lee, K.K., McAllister, D.A., Hunter, A., Nair, H., Whiteley, W., Langrish, J.P., Newby, D.E. and Mills, N.L. (2015). Short-term exposure to air pollution and stroke: systematic review and meta-analysis. *British Medical Journal*, 350, h1295.

Shamsi, R.S.A. (2007). *Monitoring the Impact of Tropospheric Ozone on Some Crops in Lahore, Pakistan.* Malé Biomonitoring Campaign, Regional Training Workshop, Dhaka, Bangladesh, 15–16 August 2007.

Shang, Y., Sun, Z., Cao, J., Wang, X., Zhong, L., Bi, X., Li, H., Liu, W., Zhu, T. and Huang, W. (2013). Systematic review of Chinese studies of short-term exposure to air pollution and daily mortality. *Environment International*, 54 (Supplement C), 100–111.

Shao, A.Z., Yang, Z. and Cui, H. (2017). *Cost-Benefit Analysis Of Early Implementation of the China 6 Light-Duty Vehicle Emission Standard in Guangdong Province*. International Council on Clean Transportation, Washington, DC, USA.

Sharma, A.R., Kharol, S.K. and Badarinath, K.V.S. (2011). Variation in atmospheric aerosol properties over a tropical urban region associated with biomass-burning episodes – a study using satellite data and ground-based measurements. *International Journal of Remote Sensing*, 32(7), 1945–1960.doi: 10.1080/01431161003639686.

Shi, G.Y., Yang, L.X., Wang, Y.X., Kobayashi, K., Zhu, J.G., Tang, H.Y., Pan S.T., Chen, T., Liu, G. and Wang, Y.L. (2009). Impact of elevated ozone concentration on yield of four Chinese rice cultivars under fully open-air field conditions. *Agriculture, Ecosystems and Environment*, 131(3/4), 178–184.

Shindell, D., Borgford-Parnell, N., Brauer, M., Haines, A., Kuylenstierna, J.C.I., Leonard, S.A., Ramanathan, V., Ravishankara, A., Amann, M. and Srivastava, L. (2017). A climate policy pathway for near- and long-term benefits. *Science*, 356, 493–4.

Shindell, D., Kuylenstierna, J.C.I., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S.C., Muller, N., Janssens-Maenhout, G., Raes, F., Schwartz, J., Faluvegi, G., Pozzoli, L., Kupiainen, K., Höglund-Isaksson, L., Emberson, L., Streets, D., Ramanathan, V., Hicks, K., Oanh, N.T.K., Milly, G., Williams, M., Demkine, V. and Fowler, D. (2012). Simultaneously mitigating near-term climate change and improving human health and food security. *Science*, 335, 183–9. doi:10.1126/*science*.1210026.

Shine, K. (2009). The global warming potential – the need for an interdisciplinary retrial. *Climatic Change*, 96, 467–72.

Shine, K.P., Berntsen, T.K., Fuglestvedt, J.S. and Sausen, R. (2005). Scientific issues in the design of metrics for inclusion of oxides of nitrogen in global climate agreements. *Proceedings of the National Academy of Sciences of the United States of America*, 102, 15768–73.

Shoemaker, J.K., Schrag, D.P., Molina, M.J. and Ramanathan, V. (2013). What role for short-lived climate pollutants in mitigation policy? *Science*, 342, 1323–4.

Sicard, P., De Marco, A., Dalstein-Richier, L., Tagliaferro, F., Renou, C. and Paoletti, E. (2016). An epidemiological assessment of stomatal ozone flux-based critical levels for visible ozone injury in Southern European forests. *Science of the Total Environment*, 541, 729–741.

Siddharthan, T., Grigsby, M.R., Goodman, D., Chowdhury, M., Rubinstein, A., Irazola, V., Gutierrez, L., Miranda, J.J., Bernabe-Ortiz, A., Alam, D., Kirenga, B., Jones, R., van Gemert, F., Wise, R.A. and Checkley, W. (2018). Association between household air pollution exposure and chronic obstructive pulmonary disease outcomes in 13 low- and middle-income country settings. *American Journal of Respiratory and Critical Care Medicine*, 197, 611–620.

Silva, R.A., Adelman, Z., Fry, M.M. and West, J.J. (2016). The impact of individual anthropogenic emissions sectors on the global burden of human mortality due to ambient air pollution. *Environmental Health Perspectives*, 124(11), 1776–1784. doi:10.1289/EHP177.

Singh, A.A., Agrawal, S.B., Shahi, J.P. and Agrawal, M. (2014). Assessment of growth and yield losses in two Zea mays L. cultivars (quality protein maize and non-quality protein maize) under projected levels of ozone. *Environmental Science and Pollution Research*, 21, 2628–2641.

Singh P., Singh, S., Agrawal, S.B. and Agrawal, M. (2012). Assessment of the interactive effects of ambient O_3 and NPK levels on two mustard varieties (Brassica campestris L.) using open top chambers. *Environmental Monitoring and Assessment*, 184, 5863–5874.

Singh, E., Tiwari, S. and Agrawal, M. (2010). Variability in antioxidant and metabolite levels, growth and yield of two soybean varieties: an assessment of anticipated yield losses under projected elevation of ozone. *Agriculture, Ecosystems and Environment*, 135, 168–177.

Sinha, B., Singh Sangwan, K., Maurya, Y., Kumar,V., Sarkar, C., Chandra, B.P. and Sinha, V. (2015). Assessment of crop yield losses in Punjab and Haryana using 2 years of continuous in situ ozone measurements. *Atmospheric Chemistry and Physics*, 15, 9555–9576.

Sitch, S., Cox, P.M., Collins, W.J. and Huntingford, C. (2007). Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. *Nature*, 448, 791–794.

Skodvin, T. and Fuglestvedt, J.S. (1997). A comprehensive approach to climate change: political and scientific considerations. *Ambio*, 26, 351–8.

Smith, W.H. (1977). Removal of atmospheric particulates by urban vegetation: implications for human and vegetative health. *The Yale Journal of Biology and Medicine*, 50, 185–197.

Steiner, A. and Chameides, W. (2005). Aerosol-induced thermal effects increase modelled terrestrial photosynthesis and transpiration. *Tellus B: Chemical and Physical Meteorology*, 57, 404–411.

Stevenson, D.S., Young, P.J., Naik, V., Lamarque, J.F., Shindell, D.T., Voulgarakis, A., Skeie, R.B., Dalsoren, S.B., Myhre, G., Berntsen, T.K., Folberth, G.A., Rumbold, S.T., Collins, W.J., MacKenzie, I.A., Doherty, R.M., Zeng, G., van Noije, T.P.C., Strunk. A., Bergmann, D., Cameron-Smith, P., Plummer, D.A., Strode, S.A., Horowitz, L., Lee, Y.H., Szopa, S., Sudo, K., Nagashima, T., Josse, B., Cionni, I., Righi, M., Eyring, V., Conley, A., Bowman, K.W., Wild, O. and Archibald, A. (2013). Tropospheric ozone changes, radiative forcing and attribution to emissions in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP). *Atmospheric Chemistry and Physics*, 13, 3063–85. doi.org/10.5194/acp-13-3063-2013.

Stieb, D.M., Chen, L., Eshoul, M. and Judek, S. (2012). Ambient air pollution, birth weight and preterm birth: a systematic review and meta-analysis. *Environmental Research*, 117, 100–111. doi:10.1016/j.envres.2012.05.007.

Stjern, C.W., Samset, B.H., Myhre, G., Forster, P.M., Hodnebrog, Ø., Andrews, T., Boucher, O., Faluvegi, G., Iversen, T., Kasoar, M., Kharin, V., Kirkevåg, A., Lamarque, J.F., Olivié, D., Richardson, T., Shawki, D., Shindell, D., Smith, C.J., Takemura, T. and Voulgarakis, A. (2017). Rapid adjustments cause weak surface temperature response to increased black carbon concentrations. *Journal of Geophysical Research: Atmospheres*, 122(21), 11462–11481. doi:10.1002/2017JD027326.

Stohl, A., Aamaas, B., Amann, M., Baker, L.H., Bellouin, N., Berntsen, T.K., Boucher, O., Cherian, R., Collins, W., Daskalakis, N., Dusinska, M., Eckhardt, S., Fuglestvedt, J.S., Harju, M., Heyes, C., Hodnebrog, Ø., Hao, J., Im, U., Kanakidou, M., Klimont, Z., Kupiainen, K., Law, K.S., Lund, M.T., Maas, R., MacIntosh, C.R., Myhre, G., Myriokefalitakis, S., Olivié, D., Quaas, J., Quennehen, B., Raut, J.C., Rumbold, S.T., Samset, B.H., Schulz, M., Seland, Ø., Shine, K.P., Skeie, R.B., Wang, S., Yttri, K.E. and Zhu, T. (2015). Evaluating the climate and air quality impacts of short-lived pollutants. *Atmospheric Chemistry and Physics*, 15, 10529–66.

Sun, J., Zhou, T., Liu, M., Chen, Y., Shang, H., Zhu, L., Shedayi, A.A., Yu, H., Cheng, G., Liu, G., Xu, M., Deng, W., Fan, J., Lu, X. and Sha, Y. (2018). Linkages of the dynamics of glaciers and lakes with the climate elements over the Tibetan Plateau. *Earth-Science Reviews*, 185, 308–324: https://doi.org/10.1016/j.earscirev.2018.06.012.

Syed, F.S., Körnich, H. and Tjernström, M. (2012). On the fog variability over South Asia. *Climate Dynamics*, 39(12), 2993–3005.

Tai, A.P.K., Martin, M.V. and Heald, C.L. (2014). Threat to future global food security from climate change and ozone air pollution. *Nature Climate Change*, 3, 817–821.

Takamatsu, T., Sase, H. and Takada, J. (2001). Some physiological properties of Cryptomeria japonica leaves from Kanto, Japan: potential factors causing tree decline. *Canadian Journal of Forest Research*, 31, 663–672.

Tanaka, K. and O'Neill, B.C. (2018). Paris Agreement zero emissions goal is not always consistent with 2°C and 1.5°C temperature targets. *Nature Climate Change*, 8, 319–324. doi:10.1038/s41558-018-0097-x.

Tanaka, K. and Raddatz, T. (2011). Correlation between climate sensitivity and aerosol forcing and its implication for the "climate trap". *Climatic Change*, 109, 815–25.

Tanaka, K., Peters, G.P. and Fuglestvedt, J.S. (2010). Policy Update – Multicomponent climate policy: why do emission metrics matter? *Carbon Management*, 1, 191–7.

Tang, H.Y., Takigawa, M., Liu, G., Zhu, J. and Kobayashi, K. (2013). A projection of ozone-induced wheat production loss in China and India for the years 2000 and 2020 with exposure-based and flux-based approaches. *Global Change Biology*, 19, 2739–2752.

Thiering, E. and Heinrich, J. (2015). Epidemiology of air pollution and diabetes *Trends in Endocrinology & Metabolism*, 26, 384–394. doi:10.1016/j.tem.2015.05.002.

Thurston, G. and Lippmann, M. (2015). Ambient particulate matter air pollution and cardiopulmonary diseases. *Seminars in Respiratory and Critical Care Medicine*, 36(3), 422–32.

Tie, Z., Huang, R-J., Dai, W., Gao, J., Long, X., Su, X., Zhao, S., Wang, Q. and Li, G. (2016). Effect of heavy haze and aerosol pollution on rice and wheat productions in China. *Scientific Reports*, 6, 29612. doi:10.1038/srep29612.

Tian, R., Chen, J., Sun, X., Li, D.; Liu, C. and Weng, H. (2018). Algae explosive growth mechanism enabling weather-like forecast of harmful algal blooms. *Scientific Reports*, 8, 9923. doi:10.1038/s41598-018-28104-7.

Tomer, R., Bhatia, A., Kumar, V., Kumar, A., Singh, R., Singh, B. and Singh, S.D. (2015). Impact of elevated ozone on growth, yield and nutritional quality of two wheat species in northern India. *Aerosol and Air Quality Research*, 15, 329–340. doi:10.4209/aaqr.2013.12.0354.

Tiwari, S., Rai, R. and Agrawal, M. (2008). Annual and seasonal variations in tropospheric ozone concentrations around Varanasi. *International Journal of Remote Sensing*, 29, 4499–4514.

Tripathi, R. and Agrawal, S.B. (2012). Effects of ambient and elevated level of ozone on Brassica campestris L. with special reference to yield and oil quality parameters. *Ecotoxicology and Environmental Safety* 85, 1–12.

UNEP (2011). *Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-lived Climate Forcers*. United Nations Environment Programme, Nairobi, Kenya.

UNEP/WMO (2011). *Integrated Assessment of Black Carbon and Tropospheric Ozone*. United Nations Environment Programme, Nairobi, Kenya. World Meteorological Organization, Geneva, Switzerland. www.ccacoalition.org/ru/file/3437/download?token=EAwVDE10

UNESCAP (2016a). *2016 ESCAP Population Data Sheet: Population and Development Indicators for Asia and the Pacific*. United Nations Economic and Social Commission in Asia and the Pacific, Bangkok, Thailand. www.unescap.org/sites/default/files/SPPS%20PS%20data%20sheet%202016%20v15-2.pdf

UNESCAP (2016b). *The Economics of Climate Change in the Asia-Pacific Region*. United Nations Economic and Social Commission in Asia and the Pacific, Bangkok, Thailand. www.unescap.org/resources/economics-climate-change-asia-pacific-region

UNESCAP (2014). *World Urbanization Prospects 2014 Revision*: Highlights. United Nations Economic and Social Commission in Asia and the Pacific, Bangkok, Thailand. https://esa.un.org/unpd/wup/publications/files/wup2014-highlights.pdf

UNESCAP (2013). *Urbanization trends in Asia and the Pacific*. United Nations Economic and Social Commission in Asia and the Pacific, Bangkok, Thailand. www.unescapsdd.org/files/documents/SPPS-Factsheet-urbanization-v5.pdf

UN Habitat and UNESCAP (2015). *The State of Asian and Pacific Cities 2015: Urban Transformations Shifting Quantity to Quality*. United Nations Human Settlement Programme and United Nations Economic, Nairobi, Kenya and Social Commission in Asia and the Pacific, Bangkok, Thailand. www.unescap.org/sites/default/files/The%20State%20of%20Asian%20and%20Pacific%20Cities%202015.pdf

UNICEF (2016). *Clear the Air for Children: The Impact of Air Pollution on Children*. United Nations Children's Fund, New York City, NY, USA.

US EIA (2016). *International Energy Outlook 2016*. United States Energy Information Administration, Washington, DC, USA. www.eia.gov/outlooks/ieo/world.cfm

Van, D.T.H. and Kim Oanh, N.T. (2009). Open top chamber experiment study to assess effects of ground level ozone on local peanut cultivar in Vietnam. *International Journal of Environmental Studies*, 66(1), 101–111.

Van, D.T.H., Ishii, S. and Kim Oanh, N.T. (2009). Assessment of ozone effects on local rice cultivar by portable ozone fumigation system in Hanoi, *Vietnam Environmental Monitoring and Assessment*, 1, 569–580.

Van Dingenen, R., Raes, F., Krol, M.C., Emberson, L. and Cofala, J. (2009). The global impact of O_3 on agricultural crop yields under current and future air quality legislation. Atmospheric Environment, 43, 604–618.

Van Donkelaar, A., Martin, R.V., Brauer, M., Hsu, N.C., Kahn, R.A., Levy, R.C., Lyapustin, A., Sayer, A.M. and Winker, D.M. (2016). Global estimates of fine particulate matter using a combined geophysical-statistical method with information from satellites, models, and monitors. *Environmental Science & Technology,* 50(7), 3762–3772.

Vaux, H.J. Jr., Balk, D., Cook, E.R., Gleick, P., Lau, W.K.-M., Levy, M., Malone, E.L., McDonald, R., Shindell, D., Thompson, L.G., Wescoat, J.L. Jr. and Williams, M.W. (2012). *Himalayan Glaciers: Climate Change, Water Resources, and Water Security*. National Academies Press, Washington, DC, USA.

Vet, R., Artz, R.S., Carou, S., Shaw, M., Ro, C.U., Aas, W., Baker, A., Bowersox, V.C., Dentener, F., Galy-Lacaux, C., Hou, A., Pienaar, J.J., Gillett, R., Forti, M.C., Gromov, S., Hara, H., Khodzher, T., Mahowald, N.M., Nickovic, S., Rao, P.S.P. and Reid, N.W. (2014). A global assessment of precipitation chemistry and deposition of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus. *Atmospheric Environment*, 93, 3–100. doi:10.1016/j.atmosenv.2013.10.060.

Vichit-Vadakan, N., Vajanapoom, N. and Ostro, B. (2008). The Public Health and Air Pollution in Asia (PAPA) project: estimating the mortality effects of particulate matter in Bangkok, Thailand. *Environmental Health Perspectives*, 116(9), 1179–1182.

Victor, D.G., Zaelke, D. and Ramanathan, V. (2015). Soot and short-lived pollutants provide political opportunity. *Nature Climate Change*, 5, 796–8.

Von Schneidemesser, E., Monks, P.S., Allan, J.D., Bruhwiler, L., Forster, P., Fowler, D., Lauer, A., Morgan, W.T., Paasonen, P., Righi, M., Sindelarova, K. and Sutton, M.A. (2015). Chemistry and the linkages between air quality and climate change. *Chemical Reviews*, 115, 3856–97.

Wahid, A. (2006). Influence of atmospheric pollutants on agriculture in developing countries: A case study with three new wheat varieties in Pakistan. *Science of the Total Environment*, 371, 304–313.

Wahid, A., Milne, E., Shamsi, S.R.A., Ashmore, M.R. and Marshall, F.M. (2001). Effects of oxidants on soybean growth and yield in the Pakistan, Punjab, *Environmental Pollution*, 113, 271–280.

Wahid, A., Maggs, R., Shamsi, S.R.A., Bell, J.N.B. and Ashmore, M.R. (1995). Effects of air pollution on rice yield in the Pakistan Punjab. Environmental Pollution, 90, 323–329.

Wang, X. and Mauzerall, D.L. (2004). Characterizing distributions of surface ozone and its impact on grain production in China, Japan and South Korea: 1990 and 2020. *Atmospheric Environment*, 38, 4383–4402.

Wang, R., Goll, D., Balkanski, Y., Hauglustaine, D., Boucher, O., Ciais, P., Janssens, I., Penuelas, J., Guenet, B., Sardans, J., Bopp, L., Vuichard, N., Zhou, F., Li, B., Piao, S., Peng, S., Huang, Y. and Tao, S. (2017). Global forest carbon uptake due to nitrogen and phosphorus deposition from 1850 to 2100. *Global Change Biology*, 23, 4854–4872. https://doi.org/10.1111/gcb.13766.

Wang, T., Xue, L., Brimblecombe, P., Lam, Y.F., Li, L. and Zhang, L. (2016). Ozone pollution in China: A review of concentrations, meteorological influences, chemical precursors, and effects. *Science of the Total Environment*, 575, 1582–1596. doi.org/10.1016/j.scitotenv.2016.10.081.

Wang. Y., Song, Q., Frei, M., Shao, Z. and Yang, L. (2014). Effects of elevated ozone, carbon dioxide, and the combination of both on the grain quality of Chinese hybrid rice. *Environmental Pollution*, 189, 9–17.

Wang, X.K., Zhang, Q.Q., Zheng, F.X., Zheng, Q.W., Yao, F.F., Chen, Z., Zhang, W.W., Hou, P.Q., Feng, Z.Z., Song, W.Z. and Lu, F. (2012). Effects of elevated O3 concentration on winter wheat and rice yields in the Yangtze River Delta, China. *Environmental Pollution*, 171, 118–125.

Watanabe, M., Matsuo, N., Yamaguchi, M., Matsumura, H., Kohno, Y. and Izuta, T. (2010). Risk assessment of ozone impact on the carbon absorption of Japanese representative conifers. *European Journal of Forest Research*, 129, 421–430.

Wei, X.L., Li, Y.S., Lam, K.S., Wang, A.Y. and Wang, T.J. (2007). Impact of biogenic VOC emissions on a tropical cyclone-related ozone episode in the Pearl River Delta region, China. *Atmospheric Environment*, 41, 7851–7864.

Wharton (2012). *Southeast Asian Megacities: Big Challenges, Bigger Opportunities*. Wharton, University of Pennsylvania, Philadelphia, PA, USA. https://global.wharton.upenn.edu/southeast-asian-megacities-big-challenges-bigger-opportunities

Wild, M. (2012). Enlightening global dimming and brightening. *Bulletin of the American Meteorological Society*, 27–37. https://doi.org/10.1175/BAMS-D-11-00074.1.

WHO (2018). *Burden of disease from the joint effects of household and ambient Air pollution for 2016*. World Health Organization, Geneva, Switzerland. https://www.who.int/airpollution/data/AP_joint_effect_BoD_results_May2018.pdf

WHO (2016). *Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease*. World Health Organization, Geneva, Switzerland.

WHO (2014). *Burden of Disease from Household Air Pollution for 2012: Summary of Results*. World Health Organization, Geneva, Switzerland. http://www.who.int/phe/health_topics/outdoorair/databases/FINAL_HAP_AAP_BoD_24March2014.pdf

WHO (2006). *Air Quality Guidelines: Global Update 2005*. World Health Organization, Geneva, Switzerland.

WHO (2002). *Indoor Air Pollution, Health, and the Burden of Disease: Indoor Air Thematic Briefing 2*. World Health Organization, Geneva, Switzerland. www.who.int/indoorair/info/briefing2.pdf

Wild, O., Prather, M.J. and Akimoto, H. (2001). Indirect long-term global radiative cooling from NO_x emissions. *Geophysical Research Letters*, 28, 1719–22.

Williams, M. (2012). Tackling climate change: what is the impact on air pollution? *Carbon Management*, 3, 511–9.

Williams, K.N., Northcross, A.L. and Graham, J.P. (2015). Health impacts of household energy use: indicators of exposure to air pollution and other risks. *Bulletin of the World Health Organization*, 93 (7), 507–8.

Wong, C.M., Tsang, H., Lai, H.K., Thach, T.Q., Thomas, G.N., Chan, K.P., Lee, S.Y., Ayres, J.G., Lam, T.H. and Leung, W.K. (2016a). STROBE-long-term exposure to ambient fine particulate air pollution and hospitalization due to peptic ulcers. *Medicine* (Baltimore), 95(18), e3543.

Wong, C.M., Tsang, H., Lai, H.K., Thomas, G.N., Lam, K.B., Chan, K.P., Zheng, Q., Ayers, J.G., Lee, S.Y., Lam, T.H. and Thach, T.Q. (2016b). Cancer mortality risks from long-term exposure to ambient fine particles. Cancer Epidemiology, *Biomarkers & Prevention*, 25(5), 839–845.

Wong, C.M., Ou, C.Q., Chan, K.P., Chau, Y.K., Thach, T.Q., Yang, L., Chung, R.Y., Thomas, G.N., Peiris, J.S.M., Wong, T.W., Hedley, A.J. and Lam, T.H. (2008). The effects of air pollution on mortality in socially deprived urban areas in Hong Kong, China. *Environmental Health Perspectives*, 116(9), 1189–1194.

World Bank (2016). *The Cost of Air Pollution: Strengthening the Economic Case for Action*. World Bank Group, Washington, DC, USA.

World Bank (2014a). *$PM_{2.5}$ air pollution, mean annual exposure (micrograms per cubic meter)*. World Bank, Washington, DC, USA. https://data.worldbank.org/indicator/EN.ATM.PM25.MC.M3

World Bank (2014b). World Development Indicators. World Bank, Washington, DC, USA. https://datacatalog.worldbank.org/dataset/world-development-indicators

World Bank Group and IHME (2016). *The Cost of Air Pollution: Strengthening the Economic Case for Action*. Washington, DC, and Seattle, WA, USA. http://documents.worldbank.org/curateden/781521473177013155/pdf/108141-REVISED-Cost-of-PollutionWebCORRECTEDfile.pdf.

Wu, G.X., Liu, Y.M., Dong, B.W., Liang, X.Y., Duan, A.M., Bao, Q. and Yu J.J. (2012a). Revisiting Asian monsoon formation and change associated with Tibetan Plateau forcing: I. Formation. *Climate Dynamics*, 39(5), 1169–1181. doi:10.1007/s00382-012-1334-z.

Wu, G., Liu, Y., He, B., Bao, Q., Duan, A. and Jin, F-F. (2012b). Thermal controls on the Asian summer monsoon. *Scientific Reports*, 2, 404.

Wu, G., Liu, Y., Zhang, Q., Duan, A., Wang, T., Wan, R., Liu, X., Li, W., Wang, Z. and Liang, X. (2007). The influence of mechanical and thermal forcing by the Tibetan Plateau on Asian climate. *Journal of Hydrometeorology* 8, 770–789. doi:10.1175/JHM609.1.

Xia, J.Y., Niu, S.L. and Wan, S.Q. (2009). Response of ecosystem carbon exchange to warming and nitrogen addition during two hydrologically contrasting growing seasons in a temperate steppe. *Global Change Biology*, 15, 1544e1556.

Xiao, C.D., Qin, D., Yao, T., Ding, Y., Liu, S. and Zhao, L. (2008). Progression observation of cryospheric components and climate-related studies in China. *Advances in Atmospheric Sciences*, 25, 164–80.

Xu, X.K., Han, L., Luo, X.B., Liu, Z.R. and Han, S.J. (2009). Effects of nitrogen addition on dissolved N_2O and CO_2, dissolved organic matter, and inorganic nitrogen in soil solution under a temperate old-growth forest. *Geoderma*, 151, 370e377.

Xu, G.L., Mo, J.M., Zhou, G.Y. and Fu, S.L. (2006). Preliminary response of soil fauna to simulated N deposition in three typical subtropical forests. *Pedosphere*, 16, 596e601.

Yamaguchi, M., Inada, H., Satoh, R., Hoshino, D., Nagasawa, A., Negishi, Y., Sasaki, H., Nouchi, I., Kobayashi, K. and Izuta, T. (2008). Effects of ozone on growth, yield and leaf gas exchange rates of two Japanese cultivars of rice (*Oryza sativa L.*). *Agricultural and Forest Meteorology*, 64, 131–141

Yang, J.E., Lee, W.Y., Ok, Y.S. and Skousen, J. (2009). Soil nutrient bioavailability and nutrient content of pine trees (*Pinus thunbergii*) in areas impacted by acid deposition in Korea. *Environmental Monitoring and Assessment*, 157, 43e50.

Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H. and Xu, B. (2012). Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change*, 2, 663–667.

Yao, T., Pu, J., Lu, A., Wang, Y. and Yu, W. (2007). Recent Glacier Retreat and its Impacts on Hydrological Processes on the Tibetan Plateau, China, and Surrounding Regions. *Arctic, Antarctic, and Alpine Research*, 39(4), 642–650. https://doi.org/10.1657/1523-0430(07-510)[YAO]2.0.CO;2.

Yao. T., Wang, Y., Liu, S., Pu, J., Shen, Y. and Lu, A. (2004). Recent glacial retreat in high Asia in China and its impact on water resource in Northwest China. *Science in China Series D-Earth Sciences*, 47(12), 1065–1075.

Ye, Q.H., Yao, T.D. and Naruse, R. (2008) Glacier and lake variations in the Mapam Yumco basin, western Himalayas of the Tibetan Plateau, from 1974 to 2003 using remote sensing and GIS technologies. *Journal of Glaciology*, 54(188), 933–935.

Ye, Q.H., Zhu, L.P., Zheng, H.P., Naruse, R.J., Zhang, X.Q. and Kang, S.C. (2007), Glacier and lake variations in the Yamzhog Yumco basin, southern Tibetan Plateau, from 1980 to 2000 using remote-sensing and GIS technologies. *Journal of Glaciology*, 53(183), 673–676.

Yi, Y., Billa, L. and Singh, A. (2015). Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. *Geoscience Frontiers*, 6(6), 817–823. doi:10.1016/j.gsf.2014.02.009.

Yin, P., Brauer, M., Cohen, A., Burnett, R.T., Liu, J., Liu, Y., Liang, R., Wang, W., Qi, J., Wang, L. and Zhou, M. (2017a). Long-term fine particulate matter exposure and nonaccidental and cause-specific mortality in a large national cohort of Chinese men. *Environmental Health Perspectives*, 125, 117002. https://doi.org/10.1289/EHP1673.

Yin, P., Chen, R., Wang, L., Meng, X., Liu, C., Niu, Y., Lin, Z., Liu, Y., Liu, J., Qi, J., You, J., Zhou, G. and Kan, H. (2017b). Ambient ozone pollution and daily mortality: a nationwide study in 272 Chinese cities. *Environmental Health Perspectives*, 125(11), 117006.

Yin, P., He, G., Fan, M., Chiu, K.Y., Liu, C., Xue, A., Liu, T., Pan, Y., Mu, Q. and Zhou, M. (2017c). Particulate air pollution and mortality in 38 of China's largest cities: time series analysis. *British Medical Journal*, 356.

Yonekura, T. and Izuta, T. (2017). Effects of ozone on Japanese agricultural crops. In: *Air Pollution Impacts on Plants in East Asia* [Izuta T. (eds.)]. Springer, Tokyo.

Yorifuji, T., Kashima, S. and Doi, H. (2015). Outdoor air pollution and term low birth weight in Japan. *Environment International*, 74, 106–111.

Yorifuji, T., Kashima, S., Tsuda, T., Ishikawa-Takata, K., Ohta, T., Tsuruta, K. and Doi, H. (2013). Long-term exposure to traffic-related air pollution and the risk of death from hemorrhagic stroke and lung cancer in Shizuoka, Japan. *Science of the Total Environment*, 443, 397–402.

Yu, K., Qiu, G. and Chan, K. (2018). Association of solid fuel use with risk of cardiovascular and all-cause mortality in rural China. *Journal of the American Medical Association*, 319, 1351–1361.

Yu, S., Bian, Y. and Ma, G. (1990). Discussion on relationship between masson pine decline and air pollution in Chongqing. *Journal of Environmental Sciences* (China), 10(3), 378–383 (in Chinese).

Zhang, B.N. and Kim Oanh, N.T. (2002). Photochemical smog pollution in the Bangkok metropolitan region of Thailand in relation to O3 precursor concentrations and meteorological conditions. *Atmospheric Environment*, 36, 4211–4222. doi:10.1016/S1352-2310 (02)00348-5.

Zhang, X., Ming, J., Li, Z., Wang, F., and Zhang, G. (2017). The online measured black carbon aerosol and source orientations in the Nam Co region, Tibet. *Environmental Science and Pollution Research*, 24, 25021–25033.

Zhang, W., Feng, Z., Wang, X. and Niu, J. (2012). Responses of native broadleaved woody species to elevated ozone in subtropical China. *Environmental Pollution*, 163, 149–57. doi:10.1016/j.envpol.2011.12.035.

Zhang, Q., Jimenez, J.L., Canagaratna, M.R., Allan, J.D., Coe, H., Ulbrich, I., Alfarra, M.R., Takami, A., Middlebrook, A.M., Sun, Y.L., Dzepina, K., Dunlea, E., Docherty, K., DeCarlo, P.F., Salcedo, D., Onasch, T., Jayne, J.T., Miyoshi, T., Shimono, A., Hatakeyama, S., Takegawa, N., Kondo, Y., Schneider, J., Drewnick, F., Borrmann, S., Weimer, S., Demerjian, K., Williams, P., Bower, K., Bahreini, R., Cottrell, L., Griffin, R.J., Rautiainen, J., Sun, J.Y., Zhang, Y.M. and Worsnop, D.R. (2007). Ubiquity and dominance of oxygenated species in organic aerosols in anthropogenically-influenced Northern Hemisphere midlatitudes. *Geophysical Research Letters*, 34, L13801. doi:10.1029/2007GL029979.

Zhang, L., Cao, H., Shen, Y., Gao, J., Shu, J., Liu, L. and Xiong, Y. (1998). Effect of acidic deposition on agriculture of Jiangsu, Zhejiang, Anhui, Fujian, Hunan, Hubei and Jiangxi Province – damage to agricultural ecosystem. *China Environmental Science*, 18(1), 12–15 (in Chinese).

Zheng, F., Wang, X., Zhang, W., Hou, P., Lu, F., Du, K. and Sun, Z. (2013). Effects of elevated O3 exposure on nutrient elements and quality of winter wheat and rice grain in Yangtze River Delta, China. *Environmental Pollution*, 179, 19–26.

Zhou, X., Zhou, J., Wang, Y., Peng, B., Zhu, J., Yang, L. and Wang, Y. (2015). Elevated tropospheric ozone increased grain protein and amino acid content of a hybrid rice without manipulation by planting density. *Journal of the Science of Food and Agriculture*, 95, 72–78.

Zhu, X.K., Feng, Z.Z., Sun, T.F., Liu, X.C., Tang, H.Y., Zhu, J.G., Guo, W.S. and Kobayashi, K. (2011). Effects of elevated ozone concentration on yield of four Chinese cultivars of winter wheat under fully open-air field conditions. *Global Change Biology*, 17, 2697–2706.

Chapter 2

Adams, R.M., Glyer, J.D., Johnson, S.L. and McCarl, B.A. (1989). A reassessment of the economic effects of ozone on United States agriculture. *J. Air Pollut. Control Assoc.*, 39, 960-968.

Ainsworth, E.A., Yendrek, C.R., Sitch, S., Collins, W.J. and Emberson, L.D. (2012). The effects of tropospheric ozone on net primary productivity and implications for climate change. *Annual Review of Plant Biology*, 63, 637–661. doi:10.1146/annurev-arplant-042110-103829.

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Binh, N.T., Posch, M., Rafaj, P., Sander, R., Schöpp, W., Wagner, F. and Winiwarter, W. (2011). Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. *Environmental Modelling and Software*, 26, 1489–1501. doi:10.1016/j.envsoft.2011.07.012.

Anenberg, S.C., Horowitz, L.W., Tong, D.Q. and West, J.J. (2010). An estimate of the global burden of anthropogenic ozone and fine particulate matter on premature human mortality using atmospheric modeling. *Environmental Health Perspectives*, 118, 1189–1195. doi:10.1289/ehp.0901220.

Balakrishnan, K., Ghosh, S., Ganguli, B., Sambandam, S., Bruce, N., Barnes, D.F. and Smith, K.R. (2013). State and national household concentrations of PM2.5 from solid cookfuel use: results from measurements and modelling in India for estimation of the Global Burden of Disease. *Environmental Health*, 12, 77. doi:10.1186/1476-069X-12-77.

Burnett, R.T., Pope, C.A. III, Ezzati, M., Olives, C., Lim, S.S., Mehta, S., Shin, H.H., Singh, G., Hubbell, B., Brauer, M., Anderson, H.R., Smith, K.R., Balmes, J.R., Bruce, N.G., Kan, H., Laden, F., Prüss-Ustün, A., Turner, M.C., Gapstur, S.M., Diver, W.R. and Cohen, A. (2014). An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environmental Health Perspectives*, 122 (4), 397–403. doi:10.1289/ehp.1307049.

CIESIN (2005). *Gridded Population of the World*, Version 3 (GPWv3). Center for International Earth Science Information Network (CIESIN), Columbia University, United Nations Food and Agriculture Programme (FAO) and Centro Internacional de Agricultura Tropical (CIAT).

Cohen, A.J., Brauer, M., Burnett, R.T., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope, C.A., Shin, H., Straif, K., Shaddick, G., Thomas, M., van Dingenen, R., van Donkelaar, A., Vos, T., Murray, C.J.L. and Forouzanfar, M.H. (2017). Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: An analysis of data from the Global Burden of Diseases Study 2015. *The Lancet*, 389, May 13. doi: 10.1016/S0140-6736(17)30505-6.

Dey, S., Di Girolamo, L., van Donkelaar, A., Tripathi, S.N., Gupta, T. and Mohan, M. (2012) Variability of outdoor fine particulate (PM2.5) concentration in the Indian Subcontinent: A remote sensing approach. *Remote Sensing of Environment*, 127, 153–161. doi: 10.1016/j.rse.2012.08.021.

Emberson, L.D., Büker, P., Ashmore, M.R., Mills, G., Jackson, L.S., Agrawal, M., Atikuzzaman, M.D., Cinderby, S., Engardt, M., Jamir, C., Kobayashi, K., Oanh, N.T K., Quadir, F. and Wahid, A. (2009). A comparison of North American and Asian exposure-response data for ozone effects on crop yields. *Atmospheric Environment*, 43, 1945–1953.

Feng, Z. and Kobayashi, K. (2009). Assessing the impacts of current and future concentrations of surface ozone on crop yield with meta-analysis. *Atmospheric Environment*, 43, 1510–1519. doi: 10.1016/j.atmosenv.2008.11.033.

Forouzanfar, M.H., Afshin, A., Alexander, L.T., *et al*. (2016). Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2015: a systematic analysis for the Global Burden of Disease study 2015. *Lancet*, 388, 1659–1724. doi:10.1016/S0140-6736(16)31679-8.

Forouzanfar, M.H., Alexander, L., Anderson, H.R., *et al*. (2015). Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990-2013: a systematic analysis for the Global Burden of Disease study 2013. *Lancet*, 386, 2287–2323. doi:10.1016/s0140-6736(15)00128-2.

Gao, M., Han, Z., Liu, Z., Li, M., Xin, J., Tao, Z., Li, J., Kang, J.-E., Huang, K., Dong, X., Zhuang, B., Li, S., Ge, B., Wu, Q., Cheng, Y., Wang, Y., Lee, H-J.,Kim, C.-H., Fu, J.S., Wang, T., Chin, M., Woo, J.-H., Zhang, Q., Wang, Z. and Carmichael, G.R. (2018). Air quality and climate change, Topic 3 of the Model Inter-Comparison Study for Asia Phase III (MICS-Asia III) – Part 1: Overview and model evaluation. *Atmospheric Chemistry and Physics*, 18, 4859–4884. doi:10.5194/acp-18-4859-2018.

Gaughan, A.E., Stevens, F.R., Linard, C., Jia, P. and Tatem, A.J. (2013). High resolution population distribution maps for Southeast Asia in 2010 and 2015. *PLoS ONE*, 8, e55882. doi:10.1371/journal.pone.0055882.

Giglio, L., Randerson, J.T. and van der Werf, G.R. (2013). Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). *Journal of Geophysical Research*, 118, 317–329. doi:10.1002/jgrg.20042.

GIZ (2014). *Consumption and Emission Inventory of Fluorinated Greenhouse Gases (CFC, HCFC and HFC) in Mexico*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Bonn, Germany.

Guenther, A., Karl, T., Harley, P., Wiedinmyer, C., Palmer, P.I., and Geron, C. (2006). Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature). *Atmospheric Chemistry and Physics*, 6, 3181–3210. doi:10.5194/acp-6-3181-2006.

Hoesly, R.M., Smith, S.J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T.J., Seibert, J., Vu, L., Andres, R.J., Bolt, R.M., Bond, T.C., Dawidowski, L., Kholod, N., Kurokawa, J., Li, M., Liu, L., Lu, Z., Moura, M.C.P., O'Rourke, P.R. and Zhang, Q. (2017). Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emission Data System (CEDS). *Geoscientific Model Development Discussions*. doi:10.5194/gmd-2017-43.

Höglund-Isaksson, L. (2012). Global anthropogenic methane emissions 2005-2030: technical mitigation potentials and costs. *Atmospheric Chemistry and Physics*, 12, 9079–9096.

Hordijk, L. and Amann, M. (2007). How science and policy combined to combat air pollution problems. *Environmental Policy and Law*, 37, 336–340.

Hudman, R.C., Moore, N.E., Mebust, A.K., Martin, R.V., Russell, A.R., Valin, L.C. and Cohen, R.C. (2012). Steps towards a mechanistic model of global soil nitric oxide emissions: implementation and space based-constraints. *Atmospheric Chemistry and Physics*, 12, 7779–7795. doi:10.5194/acp-12-7779-2012.

IEA WEO (2016). *World Energy Outlook Special Report: Energy and Air Pollution*. International Energy Agency, Paris, France.

Jerrett, M., Burnett, R.T., Pope, C.A. III, Ito, K., Thurston, G., Krewski, D., Shi, Y., Calle, E. and Thun, M. (2009). Long-term ozone exposure and mortality. *New England Journal of Medicine*, 360, 1085–1095. doi:10.1056/NEJMoa0803894.

Keller, C.A., Long, M.S., Yantosca, R.M., Da Silva, A.M., Pawson, S. and Jacob, D.J. (2014). HEMCO v1.0: a versatile, ESMF-compliant component for calculating emissions in atmospheric models. *Geoscientific Model Development*, 7, 1409–1417. doi:10.5194/gmd-7-1409-2014.

Kiesewetter, G., Schoepp, W., Heyes, C. and Amann, M. (2015). Modelling $PM_{2.5}$ impact indicators in Europe: Health effects and legal compliance. *Environmental Modelling & Software* 74, 201e211.

Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., Borken-Kleefeld, J. and Schöpp, W. (2017). Global anthropogenic emissions of particulate matter including black carbon. *Atmospheric Chemistry and Physics*, 17, 8681–8723. doi:10.5194/acp-17-8681-2017.

Klimont, Z., Smith, S.J. and Cofala, J. (2013). The last decade of global anthropogenic sulfur dioxide: 2000–2011 emissions. *Environmental Research Letters*, 8, 014003. doi:10.1088/1748-9326/8/1/014003.

Koch, D., Schmidt, G.A. and Field, C.V. (2006). Sulfur, sea salt, and radionuclide aerosols in GISS ModelE. *Journal of Geophysical Research*, 111, D06206. doi:10.1029/2004JD005550.

Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D. and Pozzer, A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature*, 525, 367. doi:10.1038/nature15371.

Lesser, V.M., Rawlings, J.O., Spruill, S.E. and Somerville, M.C. (1990). Ozone effects on agricultural crops: statistical methodologies and estimated dose-response relationships. *Crop Science*, 30(1), 148–155.

Lim, S.S., Vos, T., Flaxman, A.D. et al. (2012). A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease study 2010. *Lancet*, 380, 2224–2260.

Miller, R.L., Schmidt, G.A., Nazarenko, L.S., Tausnev, N., Bauer, S.E., Del Genio, A., Kelley, M., Lo, K.K., Ruedy, R., Shindell, D.T., Aleinov, I., Bauer, M., Bleck, R., Canuto, V., Chen, Y-H., Cheng, Y., Clune, T.L., Faluvegi, G., Hansen, J.E., Healy, R.J., Kiang, N.Y., Koch, D., Lacis, A.A., LeGrande, A.N., Lerner, J., Menon, S., Oinas, V., Garcia-Pando, C.P., Perlwitz, J.P., Puma, M.J., Rind, D., Romanou, A., Russell, G.L., Sato, M., Sun, S., Tsigaridis, K., Unger, N., Voulgarakis, A., Yao, M-S. and Zhang, J. (2014). CMIP5 historical simulations (1850–2012) with GISS ModelE2. *Journal of Advances in Modeling Earth Systems*, 6, 441–478. doi:10.1002/ 2013MS000266.

Miller, R.L., Cakmur, R.V., Perlwitz, J., Geogdzhayev, I.V., Ginoux, P., Koch, D., Kohfeld, K.E., Prigent, C., Ruedy, R., Schmidt, G.A. and Tegen, I. (2006). Mineral dust aerosols in the NASA Goddard Institute for Space Sciences ModelE atmospheric general circulation model. *Journal of Geophysical Research*, 111, D06208. doi:10.1029/ 2005JD005796.

MoEF (2009). *Roadmap for Phase-out of HCFCs in India*. Ozone Cell, Ministry of Environment & Forests, Government of India, New Delhi.

Murray, L.T., Jacob, D.J., Logan, J.A., Hudman, R.C. and Koshak, W.J. (2012). Optimized regional and interannual variability of lightning in a global chemical transport model constrained by LIS/OTD satellite data. *Journal of Geophysical Research*, 117. D20307. doi:10.1029/2012JD017934.

Naghavi, M., Abajobir, A.A., Abbafati, C. et al. et al. (2017). Global, regional, and national age-sex specific mortality for 264 causes of death, 1980–2016: a systematic analysis for the Global Burden of Disease Study 2016. *The Lancet*, 390, 1151–1210. doi:10.1016/S0140-6736(17)32152-9.

Purohit, P. and Höglund-Isaksson, L. (2017). Global emissions of fluorinated greenhouse gases 2005–2050 with abatement potentials and costs. *Atmospheric Chemistry and Physics*, 17, 2795–2816. doi:10.5194/acp-17-2795-2017.

Pye, H.O.T., Chan, A.W.H., Barkley, M.P., and Seinfeld, J.H. (2010). Global modeling of organic aerosol: the importance of reactive nitrogen (NOx and NO3). *Atmospheric Chemistry and Physics*, 10, 11261–11276. doi:10.5194/acp-10-11261-2010.

Pye, H.O.T. and Seinfeld, J.H. (2010). A global perspective on aerosol from low-volatility organic compounds. *Atmospheric Chemistry and Physics*, 10, 4377–4401. doi:10.5194/acp-10-4377-2010.

Raes, F. and Seinfeld, J.H. (2009). New directions: climate change and air pollution abatement: a bumpy road. *Atmospheric Environment*, 43(32), 5132–5133.

Reis, S., Grennfelt, P., Klimont, Z., Amann, M., ApSimon, H., Hettelingh, J.P., Holland, M., LeGall, A.C., Maas, R., Posch, M., Spranger, T., Sutton, M.A. and Williams, M. (2012). From acid rain to climate change. *Science*, 338, 1153–1154. doi:10.1126/science.1226514.

Schmidt, G.A., Kelley, M., Nazarenko, L., Ruedy, R., Russell, G.L., Aleinov, I., Bauer, M., Bauer, S.E., Bhat, M.K., Bleck, R., Canuto, V., Chen, Y-H., Cheng, Y., Clune, T.L., Del Genio, A., de Fainchtein, R., Faluvegi, G., Hansen, J.E., Healy, R.J., Kiang, N.Y., Koch, D., Lacis, A.A., LeGrande, A.N., Lerner, J., Lo, K.K., Matthews, E.E., Menon, S., Miller, R.L., Oinas, V., Oloso, A.O., Perlwitz, J.P., Puma, M.J., Putman, W.M., Rind, D., Romanou, A., Sato, M., Shindell, D.T., Sun, S., Syed, R.A., Tausnev, N., Tsigaridis, K., Unger, N., Voulgarakis, A., Yao, M-S. and Zhang, J. (2014). Configuration and assessment of the GISS ModelE2 contributions to the CMIP5 archive. *Journal of Advances in Modeling Earth Systems*, 6, 141–184. doi:10.1002/2013MS000265.

Seltzer, K.M., Shindell, D.T., Faluvegi, G. and Murray, L.T. (2017). Evaluating modeled impact metrics for human health, agriculture growth, and near-term climate. *Journal of Geophysical Research: Atmospheres*, 122(24). doi:10.1002/2017JD026780.

Shindell, D. T. (2015), The Social Cost of Atmospheric Release, *Climatic Change*, 130, 313-326.

Shindell, D., Kuylenstierna, J.C.I., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S.C., Muller, N., Janssens-Maenhout, G., Raes, F., Schwartz, J., Faluvegi, G., Pozzoli, L., Kupiainen, K., Höglund-Isaksson, L., Emberson, L., Streets, D., Ramanathan, V., Hicks, K., Kim Oanh, N.T., Milly, G., Williams, M., Demkine, V. and Fowler, D. (2012). Simultaneously mitigating near-term climate change and improving human health and food security. *Science*, 335, 183–189. doi:10.1126/*science*.1210026.

Shindell, D.T., Lee, Y.H. and Faluvegi, G. (2016). Climate and health impacts of US emissions reductions consistent with 2°C. *Nature Climate Change*, 6(5), 503–507. doi:10.1038/nclimate2935.

Shindell, D.T., Pechony, O., Voulgarakis, A., Faluvegi, G., Nazarenko, L., Lamarque, J.-F., Bowman, K., Milly, G., Kovari, B., Ruedy, R. and Schmidt, G.A. (2013). Interactive ozone and methane chemistry in GISS-E2 historical and future climate simulations. *Atmospheric Chemistry and Physics*, 13, 2653–2689. doi:10.5194/acp-13-2653-2013.

Silva, R.A., Adelman, Z., Fry, M.M. and West, J.J. (2016a). The impact of individual anthropogenic emissions sectors on the global burden of human mortality due to ambient air pollution. *Environmental Health Perspectives*. doi:10.1289/EHP177.

Silva, R.A., West, J.J., Lamarque, J.-F., Shindell, D.T., Collins, W.J., Dalsøren, S., Faluvegi, G., Folberth, G., Horowitz, L., Nagashima, T., Naik, V., Rumbold, S.T., Sudo, K., Takemura, T., Bergmann, D., Cameron-Smith, P., Cionni, I., Doherty, R.M., Eyring, V. and Zeng, G. (2016b). The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. *Atmospheric Chemistry and Physics Discussions* 16, 1–24. doi:10.5194/acp-2015-1002.

Silva, R.A., West, J.J., Zhang, Y.Q., Anenberg, C.A., Lamarque, J.-F., Shindell, D.T., Collins, W.J, Dalsoren, S., Faluvegi, G., Folberth, G., Horowitz, L.W., Nagashima, T., Naik, V., Rumbold, S., Skeie, R., Sudo, K., Takemura, T., Bergmann, D., Cameron-Smith, P., Cionni, I., Doherty, R.M., Eyring, V., Josse, B., MacKenzie, I.A., Plummer, D., Righi, M., Stevenson, D.S., Strode, S., Szopa, S. and Zeng, G. (2013). Global premature mortality due to anthropogenic outdoor air pollution and the contribution of past climate change. *Environmental Research Letters*, 8, 3. doi:10.1088/1748-9326/8/3/034005.

Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L.D., Fagerli, H., Flechard, C.R., Hayman, G.D., Gauss, M., Jonson, J.E., Jenkin, M.E., Nyíri, A., Richter, C., Semeena, V.S., Tsyro, S., Tuovinen, J.-P., Valdebenito, Á. and Wind, P. (2012). The EMEP MSC-W chemical transport model – technical description. *Atmospheric Chemistry and Physics*, 12, 7825–7865. doi:10.5194/acp-12-7825-2012.

Turner, M.C., Jerrett, M., Pope III, C.A., Krewski, D., Gapstur, S.M., Diver, W.R., Beckerman, B.S., Marshall, J.D., Su, J., Crouse, D.L. and Burnett, R.T. (2016). Long-term ozone exposure and mortality in a large prospective study. *American Journal of Respiratory and Critical Care Medicine*, 193, 1134–1142. doi: 10.1164/rccm.201508-1633OC.

UNDESA (2017). *World Population Prospects: The 2017 Revision, Key Findings and Advance Tables*. ESA/P/WP/248. United Nations Department of Economic and Social Affairs (UNDESA), Population Division, New York, NY, USA.

UNDESA (2012). *World Urbanization Prospects: The 2011 Revision*. United Nations Department of Economic and Social Affairs (UNDESA), Population Division, New York, NY, USA.

UNDESA (2011). *World Population Prospects: The 2010 Revision*. CD-ROM Edition. United Nations Department of Economic and Social Affairs (UNDESA), Population Division, New York, NY, USA.

UNDP (2014a). *Survey of the Hydrofluorocarbon (HFC) Market in Chile*. Final report. Ministry of Environment and United Nations Development Programme, Santiago, Chile.

UNDP (2014b). *Study of the Hydrofluorocarbons (HFCs) Market in Colombia*. Final report. National Ozone Unit of Colombia, Ministry of Environment and Sustainable Development and United Nations Development Programme, Bogotá, Colombia.

UNEP (2011). Executive Committee of the Multilateral Fund for the Implementation of the Montreal Protocol. United Nations Environment Programme (UNEP), Sixty-fourth Meeting, Montreal, 25–29 July (2011).

Van Dingenen, R., Dentener, F.J., Raes, F., Krol, M.C., Emberson, L. and Cofala, J. (2009). The global impact of ozone on agricultural crop yields under current and future air quality legislation. *Atmospheric Environment* 43, 604–618. doi:10.1016/j.atmosenv.2008.10.033.

WHO GBD (2016). *Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease*. World Health Organization, Geneva, Switzerland.

Wittig, V.E., Ainsworth, E.A., Naidu, S.L., Karnosky, D.F. and Long, S.P. (2009). Quantifying the impact of current and future tropospheric ozone on tree biomass, growth, physiology and biochemistry: A quantitative meta-analysis. *Global Change Biology*, 15, 396–424. doi:10.1111/j.1365-2486.2008.01774.x.

Zender, C.S., Bian, H. and Newman, D. (2003). Mineral Dust Entrainment and Deposition (DEAD) model: description and 1990s dust climatology. *Journal of Geophysical Research*, 108, D14. doi:10.1029/2002JD002775.

Zhang, L., Jacob, D.J., Knipping, E.M., Kumar, N., Munger, J.W., Carouge, C.C., van Donkelaar, A., Wang, Y.X. and Chen, D. (2012). Nitrogen deposition to the United States: distribution, sources, and processes. *Atmospheric Chemistry and Physics*, 12, 4539–4554. doi:10.5194/acp-12-4539-2012.

Chapter 3

ADB and Clean Air Asia (2014). *Improving Air Quality Monitoring in Asia: A Good Practice Guide*. Asian Development Bank, Manila, Philippines. http://cleanairasia.org/wp-content/uploads/portal/files/improving_aqmt_in_asia.pdf

AECEN (2004). *Environmental Compliance and Enforcement in Thailand: Rapid Assessment*. https://www.aecen.org/sites/default/files/TH_Assessmemt.pdf

Agamuthu, P. and Heart, S. (2014). Sustainable waste management in Small Island Developing States. *Waste Management & Research*, 32(8), 681–82.

Andersson, K.P. and Ostrom, E. (2008). Analyzing decentralized resource regimes from a polycentric perspective. *Policy Sciences*, 41(1), 71–93. doi:10.1007/s11077-007-9055-6.

ASEAN (2017). *Roadmap on ASEAN Cooperation Towards Transboundary Haze Pollution Control with Means Of Implementation*. http://haze.asean.org/wp-content/uploads/2017/10/Roadmap-ASEAN-Haze-Free_adoptedbyCOP12.pdf

Bang, H.Q, Khue, V.H.N., Tam, N.T. and Lasko, K. (2017). Air pollution emission inventory and air quality modeling for Can Tho City, Mekong Delta, Vietnam. *Air Quality, Atmosphere & Health*, 11(1), 35–47. doi:10.1007/s11869-017-0512-x.

Bao, P.N. and Kuyama, T. (2013). Decentralized domestic wastewater management in Asia – challenges and opportunities. *WEPA Policy Brief No. 1*. WEPA-MOEJ, Ministry of Environment, Japan. http:// www.wepa-db.net/policy_briefs.htm

BEE (2018). *Standards & Labeling, Bureau of Energy Efficiency, India*. Bureau of Energy Efficiency, India. https://beeindia.gov.in/content/standards-labeling

BNEF (2017). *New Energy Outlook 2017*. Bloomberg New Energy Finance, New York, NY, USA.

BP (2017). *BP Statistical Review of World Energy*. BP, London, UK. https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review-2017/bp-statistical-review-of-world-energy-2017-full-report.pdf

Bulkeley, H. and Betsill, M. (2005). Rethinking sustainable cities: multilevel governance and the urban politics of climate change. *Environmental Politics*, 14(1), 42–63.

Carvalho, S., Andersen, S.O., Brack, D. and Sherman, N. (2014). *Alternatives to high GWP hydrofluorocarbons*. Institute for Governance and Sustainable Development, Washington, DC, USA.

Clean Air Asia (2016a). *Clean Air Management Profile – Mongolia*. Clean Air Asia, Pasig City, Philippines.

Clean Air Asia (2016b). *Guidance Framework for Better Air Quality in Asia*. Clean Air Asia, Pasig City, Philippines.

Clean Air Asia (2016c). *Vehicle Inspection & Maintenance in Asia: Status and Challenges 2016*. Clean Air Asia, Pasig City, Philippines. http://cleanairasia.org/wp-content/uploads/2016/08/Vehicle-IM-in-Asia.pdf

Clean Air Asia (2010). *Clean Air Management Profile – India*. Clean Air Asia, Pasig City, Philippines. http://cleanairasia.org/wp-content/uploads/portal/files/documents/CAMP_India_-_2010_Edition.pdf

Cohen, M.A. (1998). Monitoring and enforcement of environmental policy. *International Yearbook of Environmental and Resource Economics*, Vol. 3. https://ssrn.com/abstract=120108 or http://dx.doi.org/10.2139/ssrn.120108.

Dasgupta, S., Laplante, B., Mamingi, N. and Wang, H. (2001). Inspections, pollution prices, and environmental performance: evidence from China. *Ecological Economics*, 36(3), 487–98.

Demirbas, A., Taylan, O. and Kaya, D. (2016). Biogas production from municipal sewage sludge. Energy Sources, Part A: Recovery, *Utilization and Environmental Effects*, 1(3), 1–7. doi: 10.1080/15567036.2017.1289282.

Department of Traffic Police Ulaanbataar (2016). Data on Vehicles. http://traffic.police.gov.mn/

Du, J., and Ouyang, D. (2017). Progress of Chinese electric vehicles industrialization in 2015: a review. *Applied Energy*, 188, 529–546.

Dunlap, R.E. and Mertig, A.G. (1992). *American Environmentalism: The U.S. Environmental Movement*, 1970–1990. Taylor & Francis, Abingdon, UK.

Edwards, R.D., Liu, Y., He, G., Yin, Z., Sinton, J., Peabody, J. and Smith, K.R (2007). Household CO and PM measured as part of a review of China's National Improved Stove Program. *Indoor Air*, 17(3), 189–203.

Elder, M. and Zusman, E. (2016). Strengthening the linkages between air pollution and the Sustainable Development Goals. *IGES Policy Brief*, no. 35.

Emam, E.A. (2015). Gas Flaring in Industry: An Overview. *Petroleum & Coal,* 57(5).

Environmental Management Bureau (n.d.). *Public-Private Environmental Monitoring Scheme of Environnmental Critical Projects in the Philippines*. AECEN, Bangkok, Thailand. https://www.aecen.org/sites/default/files/CREATION OF A MULTI-PARTITE MONITORING TEAM %28MMT%29-LSD.pdf

Esty, D.C. and Winston, A.S. (2009). *Green to Gold: How Smart Companies Use Environmental Strategy to Innovate, Create Value, and Build Competitive Advantage*. Wiley, Hoboken, NJ, USA.

FAO (2014). FAOSTAT: Fertilizers. Food and Agriculture Organization of the United Nations, Rome, Italy.

Feng, L. and Wenjie, L. (2016). Legislation, plans, and policies for prevention and control of air pollution in China: achievements, challenges, and improvements. *Journal of Cleaner Production*, 112, 1549–58.

Financial Times (2017). *Oil majors move to cut methane emissions*. https://www.ft.com/content/75bd8114-cf9c-11e7-b781-794ce08b24dc

Fu, M., Liu, H., Jin, X. and He, K. (2017). National- to port-level inventories of shipping emissions in China. *Environmental Research Letters*, 12, 114024.

Gillies, J.A., Watson, J.G., Rogers, C.F., Dubois, D., Chow, J.C., Langston, R. and Sweet, J. (1999). Long-term efficiencies of dust suppressants to reduce PM_{10} emissions from unpaved roads. *Journal of the Air and Waste Management Association*, 49(1), 3–16. doi:10.1080/10473289.1999.10463779.

GMI (2013a). *Municipal Wastewater Methane: Reducing Emissions, Advancing Recovery and Use Opportunities*. Global Methane Initiative, Washington, DC, USA. https://www.globalmethane.org/documents/ww_fs_eng.pdf

GMI (2013b). *Successful Applications of Anaerobic Digestion from Across the World*. Global Methane Initiative, Washington, DC, USA. https://www.globalmethane.org/documents/GMI%20Benefits%20Report.pdf

Graham-Harrison, E. (2016). Rajshahi: the city that took on air pollution – and won. The Guardian. https://www.theguardian.com/world/2016/jun/17/rajshahi-bangladesh-city-air-pollution-won

Greenpeace East Asia (2012). Greenpeace exists because this fragile earth deserves a voice. http://www.greenpeace.org/eastasia/about/

Gunningham, N. and Rees, J. (1997). Industry self-regulation: an institutional perspective. *Law & Policy,* 19, 363–414.

Guttikunda, S., Lodoysamba, S., Bulgansaikhan, B. and Dashdondog, B. (2013). Particulate pollution in Ulaanbaatar, Mongolia. *Air Quality, Atmosphere & Health*, 6(3), 589–601.

HKEPD (2011). *Controlling Emissions from Vessels* CB(1) 625/11-12(03). Hong Kong Environmental Protection Department. http://www.legco.gov.hk/yr11-12/english/panels/ea/papers/ea1221cb1-625-3-e.pdf

IEA (2016a). *World Energy Outlook 2016 Special Report: Energy and Air Pollution*. International Energy Agency, Paris, France.

IEA (2016b). *World Energy Outlook 2016*. International Energy Agency, Paris, France.

IPCC (1997). Nitrous oxide and carbon dioxide in agriculture. In: *OECD/IPCC/IEA Phase II Development of*

IPCC Guidelines for Natural Greenhouse Gas Inventory Methodology, Workshop Report. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Islam, S.M.M., Gaihre, Y.K., Shah, A.L., Singh, U., Sarkar, M.I.U., Satter, M.A., Sanabria, J. and Biswas, J.C. (2016). Rice yields and nitrogen use efficiency with different fertilizers and water management under intensive lowland rice cropping systems in Bangladesh. *Nutrient Cycling in Agroecosystems*, 106, 143–56.

Isley, C.F. and Taylor, M.P. (2018). Air quality management in the Pacific Islands: a review of past performance and implications for future directions. *Environmental Science and Policy*, 84, 26–33. doi:10.1016/j.envsci.2018.02.013.

Jerger, D.B. (2014). Indonesia's role in realizing the goals of ASEAN's Agreement on Transboundary Haze Pollution. *Sustainable Development Law & Policy*, 14(1), 35–45, 70–74.

Jodoin, S., Duyck, S. and Lofts, K.A. (2015). Public participation and climate governance: an introduction. *Review of European, Comparative and International Environmental Law* 24(2). https://ssrn.com/abstract=2672451.

Kanokkanjana, K. and Bridhikitti, A. (2007). *Sustainable Rice Straw Management for Urban Air Pollution Reduction in Bangbuathong, Nonthaburi Province, Thailand*. Asian Institute of Technology, Pathumthani, Thailand.

Karacan, C.Ö., Ruiz, F.A., Cotè, M. and Phipps, S. (2011). Coal mine methane: a review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction. *International Journal of Coal Geology*, 86(2–3), 121–56.

Kim Oanh, N.T. (2013). Integrated approach to rice straw management for reduction of field-burning activity. In: *Integrated Air Quality Management, Asian Case Studies*. CRC Press, Boca Raton, FL, USA.

King, A. and Lenox, M. (2002). Exploring the locus of profitable pollution reduction. *Management Science*, 48, 289–299.

Kumakura, M. (2015). Revision of the Fluorocarbons Law. https://www.env.go.jp/en/focus/jeq/issue/vol09/feature.html

Lee, S.-Y., Zusman, E. and Lee, S. (2017). Tracing sustainability transitions in Seoul governance: enabling and scaling grassroots innovations. *Procedia Engineering*, 198, 293–304.

Li, C. (2002). Reduced methane emissions from large-scale changes in water management of China's rice paddies during 1980–2000. *Geophysical Research Letters*, 29(20), 1972. doi:10.1029/2002GL015370.

Li, W. (2006). Environmental governance: issues and challenges. *Environmental Law Reporter: News & Analysis*, 36(7), 10505–10525.

Liu, H., Meng, Z., Shang, Y., Lu, Z., Jin, X., Fu, M. and He, K. (2018). Shipping emission forecasts and cost-benefit analysis of China Ports and Key Regions' control. *Environmental Pollution*, 236, 49–59.

Liu, X. (2015). Case analyses of low-carbon technology transfer from the co-benefit perspective. *Asia-Pacific Tech Monitor,* Oct–Dec 2015.

Mamingi, N., Dasgupta, S., Laplante, B. and Hong, J.H. (2008). *Environmental Economics and Policy Studies*, 9(2), 67–69.

Marshall, S., Taylor, J.A., Oglesby, R.J., Larson, J.W. and Erickson, D.J. (1996). Climatic effects of biomass burning. *Environmental Software*, 13(1), 53–58.

Matsumoto, N., Elder, M. and Ogihara, A. (2015). Japan's policy to reduce emissions of volatile organic compounds: factors that facilitate industry participation in voluntary action. *Journal of Cleaner Production*, 108(A), 931–43.

Maynard, L. and Shortle, J. (2001). Determinants of cleaner technology investments in the U.S. bleached kraft pulp industry. *Land Economics*, 77(4).

Mehta, R. (2001). History, politics and technology of CNG-diesel switch in Delhi. In: *Land Use, Transportation and the Environment, The Transport Asia Project Workshop* (3–4 December 2001), Harvard University Center for the Environment, Cambridge, MA, USA. www.seas.harvard.edu/TransportAsia/Dec01Papers.htm

Mertig, A.G. and Dunlap, R.E. (2001). Environmentalism, new social movements, and the new class: a cross-national investigation. *Rural Sociology*, 66(1), 113.

Mertig, A.G. and Dunlap, R.E. (1995). Public approval of environmental protection and other new social movement goals in Western Europe and the United States. *International Journal of Public Opinion Research*, 7(2), 145.

Miller, J., Minjares, R., Dallman, T. and Lingzhi, J. (2017). *Financing the Transition to Soot-Free Urban Bus Fleets in 20 Megacities*. http://theicct.org/sites/default/files/publications/Soot-Free-Bus-Financing_ICCT-Report_11102017_vF.pdf

MoEF (2006). *National Environmental Policy 2006*. Ministry of Environment and Forests, New Delhi, India. http://www.indiawaterportal.org/sites/indiawaterportal.org/files/National Environment Policy_ MoEF_2006.pdf

MoEFCC (2018). *National Clean Air Programme*. Press Information Bureau, Government of India, Ministry of Environment, Forest and Climate Change, January 5. http://pib.nic.in/newsite/mbEresl.aspx?relid=175437

MoEFCC (2015). *Notification of Emission Standards for Power Plants in India*. Ministry of Environment, Forests and Climate Change, India. http://www.moef.gov.in/sites/default/files/Thermal plant gazette scan.pdf

Mohan, N. (2017). Haryana farmers unite to challenge ban on stubble burning, to burn paddy waste after protest in Kurukshetra. *Hindustan Times*, 9 October. https://www.hindustantimes.com/india-news/haryana-farmers-unite-to-challenge-ban-on-stubble-burning-to-burn-paddy-waste-after-protest-in-kurukshetra/story-wsLq78GrcTLoPOeLNIfkjO.html

Myers, S.L. (2018). In China's coal country, a ban brings blue skies and cold homes. *New York Times*, 10 February.

Nagata, A. (2010). *Strategies and policies for mitigating emissions from rice cultivation*. Methane to Markets Partnership Expo, 2–5 March, 2010. Delhi, India.

Napalang, S.G., Agatep, P.M.J., Navarro, A.M. and Detros, K.C. (2016). The motor vehicle user's charge: some issues and recommendations. Policy Notes, 2016, 16. https://dirp4.pids.gov.ph/websitecms/CDN/PUBLICATIONS/pidspn1616.pdf

NRDC (2012). *Leaking Profits*. Natural Resources Defense Council, Washington, DC, USA. https://www.nrdc.org/sites/default/files/Leaking-Profits-Report.pdf

NRDC, CEEW and IGSD TERI (2014). *Air Conditioners with Hydrocarbon Refrigerant – Saving Energy While Saving Money: A Profile of Energy-Efficient Propane (HC-290) Based Room Air Conditioners by Godrej & Boyce*. https://hychill.com.au/content/3-info/godrej-profile-5nov14.pdf

PCD (n.d). Pollution Control Department, Bangkok, Thailand. http://www.pcd.go.th/en_ab_about.cfm

Petrol World (2016). Petron rolls out Euro 5 diesel in Philippines and Malaysia. https://www.petrolworld.com/asia/item/26124-malaysia-euro-5-diesel-fuel-introduced-by-petron

PIB (2018). Use 5–10% of biomass pellets with coal for power generation in thermal power plants. Press Information Bureau. http://pib.nic.in/newsite/PrintRelease.aspx?relid=176388

PNGRB (2018). Data Bank. Petroleum and Natural Gas Regulatory Board, Delhi, India. http://www.pngrb.gov.in/data-bank.html

Porter, M.E. and van der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. *Journal of Economic Perspectives*, 9(4), 97–118

Pradhan, B., Lee, S.-Y. and Zusman, E. (2018). Assessing co-benefits from Nepal's brick kilns: measurement opportunities and challenges. In: *Asian Co-Benefits Partneship: Quantifying Co-Benefits in Asia: Methods and Applications*. Institute for Global Environmental Strategies, Hayama, Japan. https://pub.iges.or.jp/pub/asian-co-benefits-partnership-white-paper-2018.

Quah, E. and Varkkey, H. (2007). The political economy of transboundary pollution: mitigation forest fires and haze in Southeast Asia. In: *The Asian Community: Its Concepts and Prospects*. Soso Sha, Tokyo, Japan.

Rehfuess, E., Mehta, S. and Prüss-Üstün, A. (2006). Assessing household solid fuel use: multiple implications for the Millennium Development Goals. *Environmental Health Perspectives,* 114(3), 373–378.

Rutherford, D. and Ortolano, L. (2008). Air quality impacts of Tokyo's on-road diesel emission regulations. *Transportation Research Part D: Transport and Environment*, 13(4), 239–254.

Rye, T. (2016). *The Implementation and Effectiveness of Transport Demand Management Measures: An International Perspective*. Routledge, Abingdon, UK.

Salim, E. (2007). *The Haze: Economic and Social Ramifications*. ISEAS Regional Outlook Forum 2007. Singapore.

Simacha, W. (2015). *Thailand's Coal-Fired Power Plants*. The Institute for Energy Economics, Tokyo, Japan. https://eneken.ieej.or.jp/data/6468.pdf

Singh, S. and Prasad, R. (2015). Natural gas use may get a boost in Delhi over pollution concerns. *The Economic Times*, December 15. https://economictimes.indiatimes.com/industry/energy/oil-gas/natural-gas-use-may-get-a-boost-in-delhi-over-pollution-concerns/articleshow/50165557.cms

Sinton, J.E., Smith, K.R., Peabody, J.W., Yaping, L., Xiliang, Z., Edwards, R. and Quan, G. (2004). An assessment of programs to promote improved household stoves in China. *Energy for Sustainable Development*, 8, 33–52.

SMG (2017). *One Less Nuclear Power Plant*. Seoul Metropolitan Government, Republic of Korea. http://english.seoul.go.kr/policy-information/environment-energy/climate-environment/5-one-less-nuclear-power-plant-2/

Smith, K.R. and Deng, K. (2010). Chinese National Improved Stove Program for the 21st century to promote rural social and economic development. *Energy Policy Research*, 1, 24–25.

Smith, K.R., Shuhua, G., Kun, H. and Daxiong, Q. (2003). One hundred million improved cookstoves in China: how was it done? *World Development*, 21(6), 941–61.

SPREP (2017). Twenty Eighth SPREP Meeting of Officials, Agenda Item 12.3.1: European Union/SPREP Pacific Hazardous Waste Management Project (PacWaste) – Achievements, Evaluation and Legacy. Secretariat of the Pacific Regional Environment Programme, Apia, Samoa. https://www.sprep.org/attachments/2017SM28/Officials/English/WP%2012.3.1-PACWASTE.pdf

SPREP (2016). *Cleaner Pacific 2025: Pacific Regional Waste and Pollution Management Strategy 2016–2025*. Secretariat of the Pacific Regional Environment Programme, Apia, Samoa.

Statistical Agency of Ulaanbataar (2016). Data on Vehicles in Ulaanbataar (Нийслэлийн Автомашины Тоо, Бүтэц). file:///C:/Users/zusman/Downloads/avto_teever_2016_ulaanbaatar_2017-06.pdf

Stoves Summit (2017). *White Paper #2. In: Stoves Summit: Addressing Black Carbon and Other Emissions from Stoves Globally: Used for Both Heating and Cooking and Using Coal for Heating*. Warsaw, Poland. http://warsawstovesummit.org/wp-content/uploads/2017/03/WP2-Problem-definition-coal-heat-stoves-final-0617.pdf

Streets, D.G., Bond, T.C., Carmichael, G.R., Fernandes, S.D., Fu, Q. and He, D. (2003). An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. *Journal of Geophysical Research*, 108(D21), 8809. doi:10.1029/2002JD003093.

Sutton, M.A., Drewer, J., Móring, A., Adhya, T.K., Ahmed, A., Bhatia, A., Brownlie, W. Dragosits, U., Ghude, S.D., Hillier, J., Hooda, S., Howard, C., Jain, N., Kumar, D., Kumar, R.M., Nayak, D.R., Neeraja, C.N., Prasanna, R., Price, A., Ramakrishnan, B., Reay, D.S., Singh, R., Skiba, U., Smith, J.U., Sohi, S., Subrahmanyan, D., Surekha, K., van Grinsven, H.J.M., Vieno, M., Voleti, S.R., Pathak, H. and Raghuram, N. (2017). The Indian nitrogen challenge in a global perspective. In: *The Indian Nitrogen Assessment*, 9–28. Elsevier, Oxford, UK.

Takami, K. and Hatoyama, K. (2008). Sustainable regeneration of a car-dependent city: the case of Toyama toward a compact city. In: *Sustainable City Regions,* 183–200. Springer, Tokyo, Japan.

TLFF (2017). Tropical Landscapes Finance Facility. https://tlffindonesia.org/

UITP-India (2018). *A Glimpse of Development of Public Transport in 2017*. International Association of Public Transport. http://www.india.uitp.org/news/development-of-public-transport-sector-in-india-2017

UKP4 (2011). *Toward Zero Flaring in Indonesia: Developing Policy on Gas Flare Reduction*. President's Delivery Unit for Development Monitoring and Oversight. World Bank, Washington, DC, USA. http://siteresources.worldbank.org/INTGGFR/Resources/578035-1164215415623/3188029-1324042883839/6_Indonesia_Developing_Gas_Flaring_Reduction_Policy.pdf

UNCRD (2013). *Position Paper: Preparation for Regional Agreement on Green Freight in Asia*. United Nations Centre for Regional Development, Bali, Indonesia. http://www.uncrd.or.jp/content/documents/7EST-P5-PP.pdf

UNEP (2015). *UNEA Resolution 1/7: Strengthening the Role of UNEP in Promoting Air Quality*. UN Nations Environment Assembly, Nairobi, Kenya. https://wedocs.unep.org/bitstream/handle/20.500.11822/17135/UNEA1_Resolution7AirQuality.pdf.

UNEP (2009). *Cleaning Up Urban Bus Fleets*. United Nations Environment Programme, Nairobi, Kenya. http://staging.unep.org/transport/pcfv/PDF/Retrofit.pdf.

UNEP and CCAC (2014). *Lower-GWP alternatives in commercial and transport refrigeration: an expanded compilation of propane, CO2, ammonia and HFO case studies*. United Nations Environment Programme, Paris, France. www.ccacoalition.org/en/file/2120/download?token=N984s0ap

UNESCAP (2016). *The Economics of Climate Change in the Asia-Pacific Region*. United Nations Economic and Social Commission for Asia and the Pacific, Bangkok, Thailand. http://www.unescap.org/resources/economics-climate-change-asia-pacific-region

UNESCAP (2001). *Air Quality in Asia and the Pacific: An Analysis in Relation to National and International Standards.* United Nations Economic and Social Commission for Asia and the Pacific, Bangkok, Thailand. http://dag.un.org/handle/11176/377804

Uphoff, N.T. (2007). *The System of Rice Intensification: Using Alternative Cultural Practices to Increase Rice Production and Profitability from Existing Yield Potentials*. International Rice Commission Newsletter. Food and Agriculture Organization of the United Nations, Rome, Italy.

US EPA (2017). *Primary Sources of Methane Emissions*. United States Environmental Protection Agency, Washington, DC, USA.

US EPA (2009). *Analysis of International Best Practices for Coal Mine Methane Recovery and Utilization*. United States Environmental Protection Agency, Washington, DC, USA. https://www.epa.gov/sites/production/files/2016-03/documents/analysis_best_practices.pdf

Voltaire Palaña, A. (2016). Petron launches Euro 5 gasoline in PH. *The Manila Times*, 14 October. https://www.manilatimes.net/petron-launches-euro-5-gasoline-ph/291146/

Wang, S.X., Zhao, B., Cai, S.Y., Klimont, Z., Nielsen, C.P., Morikawa, T., Woo, J.H. Kim, Y., Fu, X., Xu, J.Y., Hao, J.M. and He, K.B. (2014). Emission trends and mitigation options for air pollutants in East Asia. *Atmospheric Chemistry and Physics*, 14, 6571–6603.

Wassmann, R., Hosen, Y. and Sumfleth, K. (2009). Reducing methane emissions from irrigated rice. *Agriculture and Climate Change: An Agenda for Negotiation in Copenhagen*, Focus 16, Brief 3.

Watson, J.G., Chow, J.C. and Pace, T.G. (2000). Fugitive dust emissions. *Crops*, 3(14), 117–35.

Wei, W., Wang, S., Hao, J. and Cheng, S. (2011). Projection of anthropogenic volatile organic compounds (VOCs) emissions in China for the period 2010–2020. *Atmospheric Environment*, 45(38), 6863–71.

Wheeler, D. (2000). *Greening Industry: New Roles for Communities, Markets, and Governments*. World Bank, Washington, DC, USA.

WHO (2016). *Burning Opportunity: Clean Household Energy for Health, Sustainable Development, and Wellbeing of Women and Children*. World Health Organization, Geneva, Switzerland.

WHO (2015). *Air Quality and Health Resolution Adopted at the Sixty-Eighth World Health Assembly*. World Health Organization, Geneva, Switzerland. www.euro.who.int/en/health-topics/environment-and-health/air-quality/news/news/2015/05/air-quality-and-health-resolution-adopted-at-the-sixty-eighth-world-health-assembly

World Bank (2013). *East Asia and Pacific Clean Stove Initiative Series*. World Bank, Washington, DC, USA.

World Bank (2011a). *Household Cookstoves, Environment, Health, and Climate Change: A New Look at an Old Problem*. World Bank, Washington, DC, USA.

World Bank (2011b). *Tools for Improving Air Quality Management: A Review of Top-down Source Apportionment Techniques and Their Application in Developing Countries*. World Bank, Washington, DC, USA. https://openknowledge.worldbank.org/handle/10986/17488

WWAP (2017). *The United Nations World Water Development Report 2017. Wastewater: The Untapped Resource*. United Nations World Water Assessment Programme, UNESCO, Paris, France.

Yamineva, Y. and Romppanen, S. (2017). Is law failing to address air pollution? Reflections on international and EU developments. *Review of European Community and International Environmental Law*, 26(3).

Yang, G. and Calhoun, C. (2007). Media, civil society, and the rise of a green public sphere in China. *China Information,* 21(2), 211–236.

Yousuf, A., Khan, M.R. and Wahid, Z.A. (2017). Business models for sustainability of biogas technology. *The Social Science*, 12(4), 609–16.

Zhao, X., Li, H., Wu, L. and Qi, Y. (2014). Implementation of energy-saving policies in China: how local governments assisted industrial enterprises in achieving energy-saving targets. *Energy Policy*, 66, 170–84.

Abbreviations

AAP	Ambient air pollution
AATH	ASEAN Agreement on Transboundary Haze Pollution
ADB	Asian Development Bank
AECEN	Asian Environmental Compliance and Enforcement Network
AGTP	Absolute Global Temperature Change Potential
Al	Aluminium
ALRI	Acute lower respiratory infection
AOT40	Accumulated ozone exposure over a threshold of 40 parts per billion
AOT60	Accumulated ozone exposure over a threshold of 60 parts per billion
APCAP	Asia Pacific Clean Air Partnership
APERC	Asia Pacific Energy Research Centre
AQI	Air Quality Index
ASEAN	Association of Southeast Asian Nations
ATS	Active tobacco smoking
BC	Black carbon
BEE	Bureau of Energy Efficiency (India)
BenMAP	Environmental Benefits Mapping and Analysis Program of the USEPA
BP	BP plc (formerly British Petroleum)
BrC	Brown Carbon
^{o}C	Degree Celsius
CAA (CAI-Asia)	Clean Air Asia (formerly Clean Air Initiative for Asian Cities)
CAS	Chinese Academy of Sciences (China)
CaCO3	Calcium carbonate
CC	Closed chamber
CCAC	Climate and Clean Air Coalition (UN Environment)
CDM	Clean Development Mechanism
CEDS	Community Emission Data System
CF	Charcoal-filtered air
CFC	Chlorofluorocarbon
CH_4	Methane
CLE	Current legislation scenario
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
COPD	Chronic obstructive pulmonary disease
CPL	Crop production loss
CTMs	Chemistry transport models
DALYs	Disability-adjusted life years
DEAD	Dust entrainment and deposition
DECAs	Domestic emission control areas (China)
DO3SE	Deposition of Ozone for Stomatal Exchange model
EDU	Ethylene diurea
EIU	Economist Intelligence Unit
EMEP	European Monitoring and Evaluation Programme
F-gas	Fluorinated gas
FACE	Free air concentration enrichment
FAO	Food and Agriculture Organization of the United Nations
GAINS	Greenhouse gas – Air pollution Interactions and Synergies model
GAEZ	Global agro-ecological zones
GBD	Global burden of disease
GCM	General circulation model
GCM	Global climate model
GDP	Gross domestic product
GEOS-Chem	Goddard Earth Observing System-chemical transport model
GFED	Global Fire Emissions Database
GHG	Greenhouse gas

GISS	Goddard Institute for Space Studies
GMAO	Global Modelling and Assimilation Office
GMI	Global Methane Initiative
GW	Gigawatt (10^9 watts)
GWP	Global warming potential
HAP	Household air pollution
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HEI	Health Effects Institute
HKHT	Hindu Kush, Karakoram, Himalaya and Tibet
HOx	Hydrogen oxides radicals
I&M	Inspection and maintenance programmes
ICCT	International Council on Clean Transport
ICLEI	International Council for Local Environmental Initiatives
ICRAF	World Agroforestry Centre (formerly International Centre for Research in AgroForestry)
IEA	International Energy Agency
IER	Integrated exposure-response
IGES	Institute for Global Environmental Strategies
IHD	Ischemic heart disease
IHME	Institute for Health Metrics and Evaluation
IIASA	International Institute for Applied Systems Analysis
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IPCC SRES A2	IPCC Special Report on Emission Scenarios A2
JICA	Japan International Cooperation Agency
J-PRISM II	Japanese Technical Cooperation Project for Promotion of Regional Initiative on Solid Waste Management, Phase II (Japan)
km^2	Square kilometre
kt	Kilotonnes (10^3 tonnes)
kWh	kilowatt (10^3 watts)-hour
LC	Lung cancer
LDAR	Leak detection and repair system
LPG	Liquefied petroleum gas
m^2	square metre
m^3	cubic metre
MEE	Ministry of Ecology and Environment (China)
MFR	Maximum technically feasible reduction
mg/m^2	Milligrams (0.001 grams) per square metre
MICS-Asia	Model Inter-Comparison Study for Asia
MMTs	Multi-partite monitoring teams (Philippines)
MODIS	Moderate Resolution Imaging Spectroradiometer
MoEF	Ministry of Environment and Forest (India)
MoEF&CC	Ministry of Environment, Forest and Climate Change (India)
Mt	Million (10^6) tonnes
M7	7-hour seasonal daytime mean measured ozone concentration
N	Nitrogen
NAMP	National Air Quality Monitoring Programme (India)
NASA	National Aeronautics and Space Administration (USA)
NBCI	National Biomass Cookstoves Initiative (India)

NDC	Nationally determined contribution
NEDO	New Energy and Industrial Technology Development Organization (Japan)
NH_3	Ammonia
NH_4+	Ammonium
NISP	National Improved Stove Program (China)
NMVOC	Non-methane volatile organic compound
NO	Nitrogen monoxide
NO_x	Nitrogen oxides (NO and NO_2)
NO_2	Nitrogen dioxide
NO_3-	Nitrate
N_2O	Nitrous oxide
NPIC	National Programme for Improved Chulhas (India)
NRDC	Natural Resources Defence Council (USA)
OC	Organic carbon
OECD	Organisation for Economic Co-operation and Development
OH	Hydroxyl radical
OTC	Open-top chamber
O_3	Ozone
P	Phosphorus
PAH	Polycyclic aromatic hydrocarbon
PAN	Peroxyacyl nitrates
PFC	Perfluorocarbon
PM	Particulate matter
$PM_{2.5}$	Particulate matter with an aerodynamic diameter of equal to and less than 2.5 micrometres (µm)
PM_{10}	Particulate matter with an aerodynamic diameter of equal to and less than 10 micrometres (µm)
POPs	Persistent organic pollutants
ppb	Parts per billion (10^9)
PPM	Primary particulate matter emissions
ppm	Parts per million (10^6)
ppm.h	The product of parts per million and hours
PSI	Pollutants Standard Index (Singapore)
PV	Photovoltaic
RC	Reference concentration
RETRO	REanalysis of TROpospheric chemical composition
RR	Rate ratios of excess mortality
RR	Relative risk
RYL	Relative yield loss
S	Sulphur
SDG	Sustainable Development Goal
SEI	Stockholm Environment Institute
SF_6	Sulphur hexafluoride
SGFE	Sustainable Green Fuel Enterprise programme (Cambodia)
SHS	Second-hand tobacco smoke
SIDS	Small Island Developing States
SLCP	Short-lived Climate Pollutant, i.e., Black carbon, methane, tropospheric ozone and hydrofluorocarbons
SMG	Seoul Metropolitan Government (Republic of Korea)
SOA	Secondary organic aerosols
SO_2	Sulphur dioxide
SO_4^{2-}	Sulphate
SPREP	Secretariat of the Pacific Regional Environment Programme
SVPCF	Special Vehicle Pollution Control Fund (Philippines)
TAA	Total amino acids
TEAA	Total essential amino acids
TEG	Triethylene glycol

TLB	Tropical Landscapes Bond (Indonesia)
TLFF	Tropical Landscapes Finance Facility (Indonesia)
TLGF	Tropical Landscapes Grant Fund (Indonesia)
TLLF	Tropical Landscapes Loan Fund (Indonesia)
TNEAA	Total non-essential amino acids
TWh	Terawatt (10^{12} watts) hours
UITP	International Association of Public Transport (India)
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNCRD	United Nations Centre for Regional Development
UNEA	United Nations Environment Assembly
UNEP	United Nations Environment Programme (UN Environment)
UNESCAP	United Nations Economic and Social Commission for Asia and the Pacific
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
US EPA	US Environmental Protection Agency (USA)
VOC	Volatile organic compound
WEO	World Energy Outlook
WHO	World Health Organization
WHR	Waste heat recovery
WMO	World Meteorological Organization
WWAP	World Water Assessment Programme (UNESCO)
UASB	Upflow anaerobic sludge blanket
µg	Microgram
µg/m^3	Micrograms per cubic metre
µm	Micrometre
1h	One hour
%	Per cent

Glossary

Term	Definition
Absorption	The process in which the energy of radiation, e.g. light, is taken up by matter. In this process, the electromagnetic energy is transformed to other forms of energy, e.g. to heat.
Accumulated ozone (O_3) exposure over a threshold (AOT) 40	Accumulated ***O_3*** exposure over a threshold of 40 parts per billion (ppb), equivalent to 80 micrograms per cubic metre (µg/m^3), for vegetation is the accumulated excess of hourly ozone concentrations above 40 ppb during a relevant growing season.
Acidification	Change in the environment's natural chemical balance caused by an increase in the concentration of acidic elements. Acidic ***atmospheric deposition*** (sometimes termed ***acid rain***) can acidify soils and aquatic ecosystems with low capacity to buffer incoming acidity.
Acid rain	Rain having a pH less than 5.6. The acidity is often the result of pollution caused mostly by SO_x and NO_x that are discharged into the ***atmosphere*** by industry. It is also created by burning coal and oil, from the operation of smelting industries and from transport. In the ***atmosphere***, these gases combine with water vapour to form acids, which then fall back to Earth in rain.
Aerosols	A collection of airborne solid or liquid particles (excluding pure water), with a typical size between 0.01 and 10 micrometers (µm) and residing in the ***atmosphere*** for at least several hours. Aerosols may be of either natural or ***anthropogenic*** origin. Aerosols may influence climate in two ways: directly through scattering and absorbing radiation, and indirectly through acting as condensation nuclei for cloud formation or modifying the optical properties and lifetime of clouds.
Albedo or surface albedo	The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo, the albedo of soils ranges from high to low and vegetation-covered surfaces and oceans have a low albedo. The Earth's planetary albedo varies mainly due to varying cloudiness, snow, ice, leaf area and land cover changes.
Ambient air quality monitoring	The systematic, long-term assessment of ***pollutant*** levels by measuring the quantity and types of certain ***pollutants*** in the surrounding outdoor air. The usual substances monitored include dust deposition, O_3, PM_{10}, $PM_{2.5}$, NO_x and SO_x.
Anaerobic digestion	A series of processes in which microorganisms break down biodegradable material in the absence of oxygen. It is commonly used for industrial or domestic purposes to manage waste and/or to release energy.
Anthropogenic	Made by people or resulting from human activities.

Term	**Definition**
Atmospheric chemistry	The study of the chemical composition and transformations of the natural planetary ***atmosphere***. It focuses upon understanding natural and ***anthropogenic*** emissions to the ***atmosphere***, the transport, chemical and physical transformations of atmospheric constituents, and the effects of air pollution and atmospheric chemistry on the environment and, particularly, on human health.
Atmospheric deposition	The transfer of substances in air to surfaces, including soil, vegetation, surface water and indoor surfaces, by dry or wet processes.
Atmosphere	The gaseous envelope surrounding the Earth.
Atmospheric forcing	The difference in the radiative forcing at the top-of-the-***atmosphere*** or tropopause and at the surface, representing heat absorbed in the lower ***atmosphere***. Gradients in heating from one place to another drive winds, and so regional differences in atmospheric forcing are closely connected to changes in regional circulation and precipitation.
Baseline	The state against which change is measured. A baseline period is the period relative to which different ***scenarios*** can be compared.
Baseline scenario	The ***baseline*** (or reference) is the state against which change is measured. It might be a current ***baseline***, in which case it represents observable, present-day conditions. It might be a future ***baseline***, which is a projected future set of conditions excluding the driving factor of interest. Alternative interpretations of the reference conditions can give rise to multiple ***baselines***.
Biodiversity	Shorthand for biological diversity. Variability among living organisms from all sources including terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within ***species***, between ***species*** and of ecosystems.
Biofuel	Biofuels are non-fossil fuels. They are energy carriers that store the energy derived from organic materials (***biomass***), including plant materials and animal waste.
Biogas	Biogas typically refers to a gas produced by the biological breakdown of organic matter in the absence of oxygen. Biogas originates from ***biogenic*** material and is a type of ***biofuel***. Biogas is produced by ***anaerobic digestion*** or fermentation of biodegradable materials such as ***biomass***, manure, sewage, ***municipal waste***, green waste, plant material and energy crops.
Biogenic	A biogenic substance is a product made by or of life forms. The term encompasses constituents, secretions, and metabolites of plants or animals.
Biomass	In the context of energy, the term biomass is also often used to refer to organic materials, such as wood by-products and agricultural wastes, which can be burned to produce energy or converted into a gas and used for fuel.

Term	Definition
Biosphere	The worldwide sum of all ecosystems. The zone of life on Earth, a closed system, apart from solar and cosmic radiation and heat from the interior of the Earth, and largely self-regulating.
Black carbon (BC)	The substance formed through the incomplete combustion of fossil fuels, ***biofuels***, and ***biomass***, which is emitted in both ***anthropogenic*** and naturally occurring soot. It consists of pure carbon in several linked forms. Black carbon warms the Earth by absorbing heat in the ***atmosphere*** and by reducing ***albedo*** – the ability to reflect sunlight – when deposited on snow and ice. Operationally defined as an ***aerosol species*** based on measurement of light ***absorption*** and chemical reactivity and/or thermal stability.
Brown clouds	High concentrations of ***particulate matter*** suspended in the ***atmosphere*** lead to light scattering, resulting in a reduction in visibility and a reddish-brown sky colouration.
Business-as-usual scenario	The ***scenario*** that examines the consequences of continuing current trends in population, economy, ***technology*** and human behaviour.
Bus rapid transit	A term applied to a variety of public transport systems using buses to provide faster, more efficient service than an ordinary bus line. Often this is achieved by making improvements to existing infrastructure, vehicles and scheduling.
Carbon cycle	All parts (reservoirs) and fluxes of C. The cycle is usually thought of as four main reservoirs of carbon connected by pathways of exchange. The reservoirs are the ***atmosphere***, terrestrial ***biosphere*** (usually including freshwater systems), oceans, and sediments (including fossil fuels). The annual movements of C, the C exchanges between reservoirs, occur because of various chemical, physical, geological, and biological processes. The ocean contains the largest pool of C near the surface of the Earth, but most of that pool is not involved with rapid exchange with the ***atmosphere***.
Carbon dioxide (CO_2) equivalent	Carbon dioxide equivalent describes how much ***global warming*** a given type and amount of ***greenhouse gas*** may cause, using the functionally equivalent amount or concentration of CO_2 as the reference.
Carbon dioxide (CO_2) fertilization	The enhancement of the growth of plants as a result of increased atmospheric CO_2 concentration. Depending on their mechanism of photosynthesis, certain types of plants are more sensitive to changes in atmospheric CO_2 concentration.
Carbon sequestration	The uptake and storage of C. Trees and plants, for example, absorb CO_2, release the O and store C.
Carbon sink	A C sink is a natural or artificial reservoir that accumulates and stores some C-containing chemical compounds for an indefinite period.

Term	Definition
Carbonaceous aerosol	***Aerosol*** consisting predominantly of organic substances and various forms of ***BC***.
Carbonaceous species	***Species*** consisting predominantly of organic substances and various forms of ***BC***. Carbonaceous ***species*** are an important contributor to the mass concentration of fine particulates ($PM_{2.5}$).
Cardiopulmonary	Having to do with the heart and lungs.
Cardiovascular disease	The class of diseases that involve the heart or blood vessels.
Chronic (medicine)	In medicine, a chronic disease is a disease that is long lasting or recurrent.
Climate change	The long-term fluctuations in temperature, precipitation, wind and all other aspects of the Earth's climate. It is also defined by the United Nations Framework Convention on Climate Change as "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".
Chlorofluorocarbons (CFCs)	Any of several organic compounds composed of C, fluorine (F), chlorine Cl) and hydrogen (H). They were formerly used widely as refrigerants, propellants, and cleaning solvents.
Clean development mechanism (CDM)	One of the three market-based mechanisms under the Kyoto Protocol to the United Nations Framework Convention on ***Climate Change*** (UNFCCC) whereby developed countries may finance ***greenhouse gas*** emissions-avoiding projects in developing countries, and receive certified emission reduction credits for doing so. These may be applied towards meeting mandatory limits on their own emissions.
Co-benefits	The positive effects that a ***policy*** or measure aimed at one objective might have on other objectives, without yet evaluating the net effect on overall social welfare. Co-benefits are often subject to uncertainty and depend on, among others, local circumstances and implementation practices. Co-benefits are often referred to as ancillary benefits.
Cohort study (long term)	A type of medical research to investigate the causes of disease and to establish links between risk factors and health outcomes by observing large groups of individuals and recording their exposure to certain risk factors to find clues as to the possible causes of disease. The word cohort means a group of people. These types of studies can be forward-looking (prospective) or backward-looking (retrospective). Prospective studies are planned in advance and carried out over a future period of time. Retrospective studies look at data that already exist and try to identify risk factors for particular conditions. Interpretations are limited because the researchers cannot go back and gather missing data. These long-term studies are sometimes called longitudinal studies.

Term	**Definition**
Compliance	A term that helps describe whether and to what extent there is adherence to an order, rule or agreement. Compliance depends on implementing policies agreed, and on whether measures are introduced to follow up on policies. Compliance is the degree to which the actors whose behaviour is targeted by the agreement, local government units, corporations, organizations or individuals, conform to the implementing obligations.
Compliance incentives	The financial means, directly or indirectly, to motivate polluters to adhere to the provisions in regulation, ***policy*** or law.
Concentration response function	See Dose-response function.
Conventional measures	Emission control actions that have been in use for a long time on frequently targeted sources of emissions such as power plants or vehicles.
Cost-benefit study/analysis	Cost-benefit study/analysis is an economic evaluation technique in which both the costs and values of all benefits and consequences from different interventions are expressed in monetary units. The purpose is to inform a decision on whether to make a change and the costs associated with it.
Cross-cutting issue	An issue that cannot be adequately understood or explained without reference to the interactions of several dimensions that are usually treated separately for ***policy*** purposes. For example, in some environmental problems economic, social, cultural and political dimensions interact with one another.
Cost effectiveness	an economic analysis that compares the relative costs and outcomes (effects) of different courses of action.
Crop residues	There are two types of agricultural crop residues. ***Field residues*** are materials left in an agricultural field or orchard after the crop has been harvested. These residues include stalks and stubble (stems), leaves, roots and seed pods. ***Process residues*** are those materials left after the processing of the crop into a usable resource. These residues include husks, seeds, bagasse, and roots.
Cryosphere	That portion of the Earth where natural materials (water, soil, etc.) occur in frozen form.
Cultivar	A cultivar is a cultivated variety of a plant that has been deliberately selected for specific desirable characteristics such as the colour and form of the flower, yield of the crop, disease resistance, etc.
Decoupling	Decoupling means removing the link between two variables. For example, resource decoupling is the delinking of economic growth and resource use and impact decoupling is the delinking of economic growth and negative environmental impacts. Decoupling can be relative, e.g. the rate of resource use increase is lower than the rate of economic growth, or absolute, e.g. resource use declines while the economy grows.

Term	Definition
Deforestation	Conversion of forested land to non-forest areas as a direct result of human activities.
Diesel particle filter (DPF)	A device designed to remove diesel ***particulate matter*** or soot from the exhaust gas of a diesel engine.
Disability-adjusted life years (DALYs)	The sum of years of potential life lost due to premature mortality and the years of productive life lost due to disability. It was developed so that non-fatal outcomes could be considered alongside mortality in the prioritization of health resources. DALYs have been used to assess the magnitude of disease, health risks and ***premature death*** both globally and at national and local levels. It can be referred to as a measurement of the gap between the current health status and an ideal health situation where the entire population lives to an advanced age, free of disease and disability – 1 DALY is equivalent to the loss of one healthy life year.
Discounting	Discounting is a financial mechanism in which a debtor obtains the right to delay payments to a creditor for a defined period of time in exchange for a charge or fee. Essentially, the party that owes money purchases the right to delay payment until some future date. The discount, or charge, is simply the difference between the original amount owed and the amount that has to be paid in the future to settle the debt.
Dose-response function	Describes the change in effect on an organism caused by differing levels of exposure (or doses) to a stressor (usually a chemical) after a certain exposure time.
Drylands	Areas characterized by lack of water, which constrain two major, linked ***ecosystem*** services: primary production and nutrient cycling. Four dryland sub-types are widely recognized: dry sub-humid, semi-arid, arid and hyper-arid, showing an increasing level of aridity or moisture deficit. Formally, this definition includes all land where the aridity index value is less than 0.65.
Ecosystem	A dynamic complex of plant, animal and micro-organism communities and their non-living environment, interacting as a functional unit.
Ecosystem services	The benefits people obtain from ***ecosystems***. These include provisioning services, such as food and water, regulating services, such as flood and disease control, cultural services, such as spiritual, recreational and cultural benefits, and supporting services, such as nutrient cycling, that maintain the conditions for life on Earth.
Effluent	In issues of water quality, refers to liquid waste (treated or untreated) discharged to the environment from sources such as industrial process and sewage treatment plants.
Emission inventory	Details the amounts and types of ***pollutants*** released into the environment.
Emission factor	A unique value for scaling emissions to activity data in terms of a standard rate of emissions per unit of activity.

Term	Definition
Emission standard	The maximum amount of discharge legally allowed from a single mobile or stationary source.
End-of-pipe measures	Methods or technologies used to remove already formed contaminants from a stream of air, water, waste, or other product. These techniques are called 'end-of-pipe' as they are normally implemented as a last stage of a process before the stream is disposed of or delivered such as scrubbers on smokestacks and catalytic convertors on automobile tailpipes that reduce emissions of ***pollutants*** after they have formed.
Energy efficiency	Refers to actions to save fuels by, for example, better building design, the modification of production processes, better selection of road vehicles and transport policies, the adoption of district heating schemes in conjunction with electrical power generation, and the use of domestic insulation and double glazing in homes.
Energy intensity	Ratio of energy consumption and economic or physical output. At the national level, energy intensity is the ratio of total domestic ***primary energy*** consumption or final energy consumption to ***gross domestic product*** or physical output. Lower energy intensity shows greater efficiency in energy use.
Enteric fermentation	A digestive process by which carbohydrates are broken down by microorganisms into simple molecules for ***absorption*** into the bloodstream of an animal. It is one of the factors in increased CH_4 emissions.
Episode (air pollution)	A period of abnormally high concentrations of air ***pollutants***, often due to low winds and temperature inversion, that can cause illness and/or death.
Eutrophication	The enrichment of an ***ecosystem*** with chemical nutrients, typically compounds containing N, P or both. Eutrophication can be a natural process in lakes, occurring as they age through geological time. Human activities can accelerate the rate at which nutrients enter ***ecosystems***. The runoff from agriculture and development, pollution from septic systems, sewers and other human-related activities increase the flux of both inorganic nutrients and organic substances into terrestrial, aquatic, and coastal marine ***ecosystems*** (including coral reefs). Eutrophication is a leading cause of impairment of many freshwater and coastal marine ***ecosystems*** in the world.
Fertilization effect (CO_2)	See ***Carbon dioxide (CO_2) fertilization***.
Flue gas desulphurization (FGD)	A ***technology*** that employs a sorbent, usually lime or limestone, to remove sulfur dioxide SO_2 from the gases produced by burning ***fossil fuels***. Flue gas desulfurization is a current state-of-the art ***technology*** for major SO_2 emitters, like such as power plants.
Food security	The 1996 World Food Summit of 1996 defined food ***security*** as existing "when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life".

Term	Definition
Free air concentration enrichment (FACE)	A method used by ecologists and plant biologists that raises the concentration of a gas of interest, such as CO_2 or O_3, in a specified area and allows the response of plant growth to be measured. Experiments using FACE are required because most studies looking at the effect of elevated CO_2 concentrations have been conducted in laboratories and where there are many missing factors including plant competition. Measuring the effect of elevated CO_2 and O_3 using FACE is a more natural way of estimating how plant growth will change in the future as the CO_2 the concentration of these gases may rises in the ***atmosphere***. FACE also allows the effect of elevated CO_2 ***pollutant*** concentrations on plants that cannot be grown in small spaces, such as trees, to be measured. FACE experiments, however, carry significantly higher costs relative to greenhouse experiments.
Fossil fuels	Coal, oil, petroleum, natural gas and other hydrocarbons are called fossil fuels because they are made of fossilized, carbon-rich plant and animal remains. These remains were buried in sediments and compressed over geologic time, slowly being converted to fuel.
Fugitive emissions	Emissions of gases or vapours from pressurized equipment due to leaks and other unintended or irregular releases, mostly from industrial activities – e.g. emissions of CH_4 escaping from oil and gas extraction not caught by a capture system. As well as the economic cost of lost commodities, fugitive emissions contribute to air pollution and ***climate change***.
Fuel switching	The substitution of one energy source for another in a particular end use or process, as a result of changing relative prices or technologies.
Global burden of disease (GBD)	A comprehensive demographic and epidemiological framework to estimate health gaps for an extensive set of causes of disease and injury, and for major risk factors, using all available mortality and health data and methods to ensure internal consistency and comparability of estimates.
General circulation model (GCM)	A global, three-dimensional computer model of the climate system which can be used to simulate human-induced ***climate change***. GCMs are highly complex and they represent the effects of such factors as reflective and absorptive properties of atmospheric water vapour, ***greenhouse gas*** concentrations, clouds, annual and daily solar heating, ocean temperatures and ice boundaries. The most recent GCMs include global representations of the ***atmosphere***, oceans, and land surface.
Global dimming	The gradual reduction in the amount of global direct irradiance at the Earth's surface that was observed for several decades after the start of systematic measurements in the 1950s. It is thought to have been caused by an increase in particulates such as sulphate ***aerosols*** in the ***atmosphere*** due to human action.
Global mean (surface) temperature	An estimate of the global mean surface air temperature. For changes over time, however, only anomalies, such as departures from a climatology, are used, most commonly based on the area-weighted global average of the sea surface temperature anomaly and the land surface air temperature anomaly.

Term	Definition
Global warming	Global warming is an average increase in the temperature of the ***atmosphere*** near the Earth's surface and in the ***troposphere***, which can contribute to changes in global climate patterns. Global warming can occur from a variety of causes, both natural and human induced. In common usage, global warming often refers to the warming that can occur as a result of increased emissions of greenhouse gases from human activities.
Global temperature change potential (GTP)	The ratio of the temperature change caused by emitting 1 kilogram (kg) of the ***species*** at the end of the period considered, to that caused by emitting 1 kg of CO_2.
Global warming potential (GWP)	The global warming potential of a gas or particle refers to an estimate of the total contribution to global warming over a particular time that results from the emission of 1 unit of that gas or particle relative to 1 unit of the reference gas, CO_2, which is assigned a value of 1. An index representing the combined effect of the differing times greenhouse gases remain in the ***atmosphere*** and their relative effectiveness in absorbing outgoing infrared radiation.
Governance	The manner in which society exercises control over resources. It denotes the mechanisms through which control over resources is defined and access is regulated. For example, there is governance through the state, the market or through civil society groups and local organizations. Governance is exercised through institutions, laws, property rights systems and forms of social organization.
Greenhouse gases (GHGs)	Gaseous constituents of the ***atmosphere***, both natural and ***anthropogenic***, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the ***atmosphere*** and clouds. This property causes the greenhouse effect. Water vapour (H_2O), CO_2, N_2O, CH_4 and O_3 are the primary greenhouse gases in the Earth's ***atmosphere***. There are also human-made greenhouse gases in the atmosphere, such as the halocarbons and other Cl and bromine (Br) containing substances. Beside CO_2, N_2O and CH_4, the ***Kyoto Protocol*** deals with sulphur hexafluoride (SF_6), HFC and PFC gases in the Earth's atmosphere.
Gross domestic product (GDP)	The sum of gross value added, at purchasers' prices, by all resident and non-resident producers in the economy, plus any taxes and minus any subsidies not included in the value of products in a country or geographic region for a given period, normally one year. Gross domestic product is calculated without deductions for depreciation of fabricated assets or depletion and degradation of natural resources.
Groundwater	Water that flows or seeps downward and saturates soil or rock, supplying springs and wells. The upper surface of the saturated zone is called the water table.
Haze	A state of atmospheric obscurity due to the presence of fine dust particles in suspension.

Term	Definition
High-emitting vehicles	Poorly tuned or defective vehicles with emissions of ***particulate matter*** many times greater than the average.
Hoffmann kiln	The most common kiln used in brick production. A Hoffmann kiln consists of a main fire passage surrounded on each side by several small rooms which contain pallets of bricks. Each room is connected to the next by a passageway carrying hot gases from the fire. This design makes for a very efficient use of heat and fuel.
Human well-being	The extent to which individuals have the ability to live the kinds of lives they have reason to value; the opportunities people have to achieve their aspirations. Basic components of human well-being include: ***security***, material needs, health, education and social relations.
Hybrids or hybrid vehicles	A hybrid vehicle use two different forms of power, such as an electric motor and an internal combustion engine, or an electric motor with a battery and fuel cells for energy storage. The basic principle is that the different motors work better at different speeds; the electric motor is more efficient at producing torque or turning power while the combustion engine is better for maintaining high speeds. Switching from one to the other yields greater fuel and ***energy efficiency*** with less consumption of fuel and fewer CO_2 emissions than a comparable conventional petrol or diesel-engined vehicle. All hybrids have the ability to generate electric current, store it and use that current to help drive the car.
Hydrocarbons	Substances containing only H and C.
Hydrochlorofluorocarbons (HFCs)	Organic compounds that contain F and H atoms and are the most common type of organofluorine compounds. They are frequently used in air conditioning and as refrigerants in place of the older CFCs such as R-12 and HCFCs such as R-21. They do not harm the ***O_3 layer*** as much as the compounds they replace, but they do contribute to global warming.
Hydrological cycle	Succession of stages undergone by water in its passage from the ***atmosphere*** to the Earth and its return to the ***atmosphere***. The stages include evaporation from land, sea or inland water; condensation to form clouds; precipitation; accumulation in the soil or in water bodies; and re-evaporation.
Incomplete combustion	A reaction or process which entails only partial burning of a fuel. Combustion is almost always incomplete and this may be due to a lack of oxygen or low temperature, preventing the complete chemical reaction.
Indoor air pollution (or household air pollution)	Air ***pollutants*** that occur within buildings or other enclosed spaces, as opposed to those occurring in outdoor, or ambient, air. Some examples of indoor air ***pollutants*** are NO_x, smoke, formaldehyde (CH_2O), and CO. The air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants. Understanding and controlling common ***pollutants*** indoors can help reduce your risk of indoor health concerns. Health

Term	Definition
	effects from indoor air ***pollutants*** may be experienced soon after exposure or, possibly, years later.
Informal (waste) sector	Informal sector in waste management context describes an individual or groups of waste pickers who collect recyclable wastes. The informal sector is also involved in other waste management activities including collecting waste from households (door-to-door collection) and bringing it to major collection points for a small fee; collecting organic waste for small-scale composting to earn money from the resulting compost's sale as a soil conditioner or fertilizer. The term informal infers unregistered, unrecognized, unprofessionalized and unmonitored by government. Therefore, it is often found that the informal sector in waste management involves child labour, practices that endanger personal health and safety. The informal sector in Asia plays an important role in waste management.
Institutions	Regularized patterns of interaction by which society organizes itself: the rules, practices and conventions that structure human interaction. The term is wide and encompassing, and could be taken to include law, social relationships, property rights and tenurial systems, norms, beliefs, customs and codes of conduct as well as multilateral environmental agreements, international conventions and financing mechanisms. Institutions could be formal (explicit, written, often having the sanction of the state) or informal (unwritten, implied, tacit, mutually agreed and accepted). Formal institutions include law, international environmental agreements, by laws and memoranda of understanding. Informal institutions include unwritten rules, codes of conduct and value systems. The term institutions should be distinguished from ***organizations***.
Integrated exposure-response function (IER)	Models that combine exposure and risk data for four sources of combustion-related pollution, namely outdoor air, second-hand smoke, household air pollution and active smoking.
Interlinkage	The cause-effect chain(s) that cross the boundaries of current environmental and environment-development challenges.
Kigali Amendment	The 2016 Kigali Amendment to the ***Montreal Protocol*** on Substances that deplete the O_3 layer aims for the phase-down of HFCs by cutting their production and consumption.
Life-cycle cost	The total cost of an item throughout its lifetime, including the sum of all recurring and non-recurring (one-time) costs over the full life span or a specified period of goods, services, structures, or systems. It includes the costs of planning, design, acquisition, operations, maintenance and disposal, less any residual value and/or purchase price, installation, operating, maintenance and upgrade costs, and remaining (residual or salvage) value at the end of ownership or its useful life.

Term	Definition
Long-lived greenhouse gases (LLGHGs)	Long-lived greenhouse gases (LLGHGs), for example, CO_2, CH_4 and N_2O, are chemically stable and persist in the ***atmosphere*** over time scales of a decade to centuries or longer, so that their emission has a long-term influence on climate. Because these gases are long lived, they become well mixed throughout the ***atmosphere*** much faster than they are removed and their global concentrations can be accurately estimated from data at a few locations. CO_2 does not have a specific lifetime because it is continuously cycled between the ***atmosphere***, oceans and land ***biosphere*** and its net removal from the ***atmosphere*** involves a range of processes with different time scales.
Long range transport (LRT)	Atmospheric transport of air ***pollutants*** within a moving air mass for a distance greater than 100 kilometres.
Measures contributing to development priority goals	The measures that were assessed and yield the greatest benefits not only to human health, agricultural crop yields and temperature increase but also contribute to the achievement of the SDGs.
Meta-analysis	A statistical analysis that combines the results of multiple scientific studies. The basic rationale behind meta-analyses is that there is a common truth behind all conceptually similar scientific studies, but which has been measured with a certain error within individual studies. Their aim is to use statistical approaches to derive a pooled estimate closest to the unknown common truth based on how this error is perceived. In essence, all existing methods yield a weighted average from the results of the individual studies and what differs is the manner in which these weights are allocated and also the manner in which the uncertainty is computed around the point estimate thus generated. In addition to providing an estimate of the unknown common truth, meta-analysis has the capacity to contrast results from different studies and identify patterns among study results, sources of disagreement among those results, or other interesting relationships that may come to light in the context of multiple studies.
Mitigation	Structural and non-structural measures undertaken to limit the adverse impact of natural hazards, environmental degradation and technological hazards.
Mitigation of climate change	In the context of ***climate change***, a human intervention to reduce the sources, or enhance the sinks of ***greenhouse gases***. Examples include using ***fossil fuels*** more efficiently for industrial processes or electricity generation; switching to sources of ***renewable energy*** (solar energy and wind power); improving the insulation of buildings and expanding forests and other sinks to remove greater amounts of CO_2 from the ***atmosphere***.
Modelled sub-regions	The sub-regions used in this report were re-grouped for scientific convenience when conducting the air modelling calculations based on sufficient available data of the sub-regions. These sub-regions have no official or administrative significance.

Term	**Definition**
Montreal Protocol	The 1987 Montreal Protocol on Substances that Deplete the ***Ozone Layer*** is an international treaty designed to protect the ***O_3 layer*** by phasing out the production of numerous substances that are responsible for its depletion. All the ***O_3 depleting substances*** controlled by the Montreal Protocol contain either Cl or Br. Some ***O_3-depleting substances*** (ODSs) are not yet controlled by the Montreal Protocol, including N_2O. For each group of ODSs, the treaty provides a timetable on which the production of those substances must be reduced and eventually eliminated.
Monsoon	Traditionally defined as a seasonal reversing wind accompanied by corresponding changes in precipitation, but it is now used to describe seasonal changes in atmospheric circulation and precipitation associated with the asymmetric heating of land and sea. Usually, the term monsoon is used to refer to the rainy phase of a seasonally-changing pattern, although technically there is also a dry phase.
Morbidity	A diseased state, disability, or poor health.
Mulch Happy seeder	An alternate ***technology***, the Happy Seeder, developed in South Asia, is a tractor-mounted machine that cuts and lifts rice straw, sews wheat into bare soil, and deposits the straw over the sown area as mulch. It can plant the wheat seed without getting jammed by the rice straw, stop farmers from burning residues without increasing field preparation costs or alter crop yields. Straw mulch reduces the amount of radiation reaching and leaving the soil surface, and therefore reduces the maximum soil temperature and increases the minimum temperature. Straw mulch also lowers soil evaporation leading to higher soil water content and/or crop water use.
Municipality	An administrative division composed of a defined territory and population.
Municipal waste	Residential solid waste and some non-hazardous commercial, institutional, and industrial wastes.
Nationally determined contributions (NDCs)	Collection of actions that countries that signed the ***Paris Agreement*** pledge to undertake to reduce national emissions and adapt to the impacts of ***climate change*** in the post-2020 period. Actions that, by ratifying the ***Paris Agreement***, each party to the UNFCCC binds itself to pursuing.
Negative forcing	Negative forcing (more outgoing energy) tends to cool a system.
Next-stage air quality measures	Measures that were assessed and yield the greatest benefits to address the remaining priority emission sources reduction in Asia after implementing Asia-wide ***conventional measures*** that proved effective in the past experience of Asian countries.
Open biomass burning	Forest, peat land fires, agriculture residue burning and outdoor cooking.

Term	Definition
Open dumping	The practice of placing waste in a disposal site at which solid wastes are disposed of in a manner that does not protect the environment. The wastes are susceptible to open burning and exposed to the elements, vectors, and scavengers.
Open top chamber (OTC)	Open top chambers are widely used to study the effects of elevated CO_2 and other atmospheric gases such as O_3 on vegetation. They are plastic enclosures, with an open top, constructed of an aluminum frame covered by panels of polyvinyl chloride plastic film. Air is pulled into the bottom of the chamber, enriched with CO_2 or O_3, and then blown through the open top of the chamber. They are relatively inexpensive to construct and maintain, however, they are not appropriate for the study of large vegetation (e.g. forest ***ecosystems***).
Organizations	Bodies of individuals with a specified common objective. Organizations can be political (political parties, governments and ministries); economic (federations of industry); social (non-governmental organizations and self-help groups) or religious (church and religious trusts). The term organizations should be distinguished from ***institutions***.
Ozone (O_3)–tropospheric or ground level O_3 and stratospheric O_3	O_3 is a triatomic molecule consisting of three oxygen (O) atoms. Tropospheric or ground-level O_3 is an air ***pollutant*** with harmful effects on vegetation and on the respiratory systems of animals. On the other hand, O_3 in the upper ***atmosphere (stratospheric O_3)*** protects living organisms by preventing damaging ultraviolet light from reaching the Earth's surface. This is also called the ***O_3 layer***, where O_3 concentrations are as high as 10 parts per million (ppm) and is a vitally important region of the atmosphere. This layer of O_3 is located approximately 20–50 kilometers above the Earth's surface. Stratospheric O_3 is important because it prevents most of the high-energy ultraviolet solar radiation from reaching the Earth's surface.
Ozone depleting substances (ODS)	Chemicals that destroy the Earth's protective ***O_3 layer*** when released into the ***atmosphere***. They include ***chlorofluorocarbons*** (CFCs), halon, carbon tetrachloride (CC_{l4}), methyl chloroform (CH_3CC_{l3}), hydrobromofluorocarbons (HBFCs), ***hydrochlorofluorocarbons*** (HCFCs), methyl bromide (CH_3Br) and bromochloromethane (CH_2BrCl)
Ozone layer	The stratosphere contains a layer in which the concentration of ***O_3*** is greatest, the so-called ***ozone*** layer. The layer extends from about 12 to 40 kilometers above the Earth's surface. The ***O_3*** concentration reaches a maximum between about 20 and 25 kilometers. This layer is being depleted by human emissions of chlorine and bromine compounds. Every year, during the southern hemisphere spring, a very strong depletion of the ***O_3*** layer takes place over the Antarctic region, caused by ***anthropogenic*** chlorine and bromine compounds in combination with the specific meteorological conditions in of that region.
Ozone-induced crop loss	Crop yields are decreased by ground-level ***O_3*** pollution, to differing extents depending on genotype and environmental conditions, and this loss is

Term	Definition
	predicted to escalate given ***climate change*** and increasing ***ozone precursor*** emissions in many areas. ***Ozone*** causes visible injury symptoms to foliage; induces early senescence and abscission of leaves; reduces stomatal aperture and thereby C uptake, and/or directly reduces photosynthetic C fixation; moderates ***biomass*** growth through C availability or more directly; decreases translocation of fixed C to edible plant parts (grains, fruits, pods, roots) due either to reduced availability at source, redirection to synthesis of chemical protectants, or reduced transport capabilities through phloem; decreased C transport to roots reduces nutrient and water uptake and affects anchorage. ***Ozone*** can moderate or bring forward flowering and induce pollen sterility. It induces ovule and/or grain abortion and finally reduces the ability of some genotypes to withstand other stresses such as drought, high vapour pressure deficit, and high photon flux density through effects on stomatal control.
Ozone precursor	Chemical compounds, such as CO, CH_4, NMVOCs and NO_x, which in the presence of solar radiation react with other chemical compounds to form O_3, mainly in the ***troposphere***.
Paris Agreement	An agreement within the United Nations Framework Convention on ***Climate Change*** (UNFCCC), dealing with greenhouse-gas-emissions ***mitigation***, adaptation, and finance, starting in the year 2020. The agreement's language was negotiated by representatives of 196 state parties at the 21st Conference of the Parties of the UNFCCC and adopted by consensus on 12 December 2015. The agreement sets out a global action plan to put the world on track to avoid dangerous ***climate change*** by limiting global warming to well below 2°C.
Particulate matter (PM)	Very small pieces of solid or liquid matter such as particles of soot, dust, fumes, mists or ***aerosols***. The physical characteristics of particles, and how they combine with other particles, are part of the feedback mechanisms of the atmosphere.The sum of all solid and liquid particles suspended in air, many of which are hazardous.
Pathway	A ***pollutant*** pathway is the route along which a particular ***pollutant*** is distributed, for example within a building or through an environmental system. An exposure pathway is a channel followed by ***pollutants*** from their source through air, soil, water, and food, to humans, animals, or their environment.
Policy	Any form of intervention or societal response. This includes not only statements of intent, such as a water policy or forest policy, but also other forms of intervention, such as the use of economic instruments, market creation, subsidies, institutional reform, legal reform decentralization and institutional development. Policy can be seen as a tool for the exercise of ***governance***. When such an intervention is enforced by the government, it is called public policy.
Policy intervention	A general inserted political and governmental process of carrying out programmes in order to fulfill specified ***policy*** objectives; a responsibility chiefly of administrative agencies.

Term	Definition
Pellet stove	A stove that burns compressed wood or ***biomass*** pellets to create a source of heat for residential and sometimes industrial spaces.
Photochemical reaction	Refers to any chemical reaction which occurs as a result of light energy from the sun.
Phytotoxicity	A term used to describe the degree of toxic effect by a compound on plant growth.
Pollutant	Any substance that causes harm to the environment when it mixes with soil, water or air
Pollutant standard index (PSI) (air quality index)	A number used to indicate the level of ***pollutants*** in air derived by averaging data collected for the past 24 hours. The PSI has been used in a number of countries. Its calculation may differ from country to country and thus different names names are used by countries for their indices such as Air Quality Health Index, Air Pollution Index and Pollutant Standards Index. The PSI is usually reported as a number on a scale of 0 to 500. The index figures enable the public to determine whether the air pollution levels in a particular location are good, moderate, unhealthy or hazardous.
Pollution	The presence of minerals, chemicals or physical properties (e.g. sound) at levels that exceed the values deemed to define a boundary between "good or acceptable" and "poor or unacceptable" quality, which is a function of the specific ***pollutant***.
Post-combustion controls	The systems that clean up exhaust gas left by burning fuel.
Poverty	The pronounced deprivation of well-being.
Precipitation	Any and all forms of water, whether liquid or solid, that fall from the ***atmosphere*** and reach the Earth's surface.
Precursor (pollutants or emission)	A compound that participates in a chemical reaction that produces another compound. Atmospheric compounds that are not ***greenhouse gases*** or ***aerosols***, but that have an effect on ***greenhouse gas*** or ***aerosol*** concentrations by taking part in physical or chemical processes regulating their production or destruction rates.
Pre-industrial	Prior to widespread industrialization and the resultant changes in the environment. Typically taken as the period before 1750.
Premature mortality or premature death	Death that occurs before the average age of death in a certain population. The World Health Organization (WHO) defines a premature death as a death that occurs before the age of 50. (World Health Report 1998). The WHO indicates that the age of 50 reflected the global average life expectancy in 1948. (World Health Report 1998) This definition exemplifies the arbitrariness of some of the definitions of premature death. To measure the ***burden of disease*** in a society, epidemiologists calculate how many years of life were

Term	Definition
	lost to premature death. This is calculated by subtracting the various ages at which individuals in a population died from the average life expectancy or an arbitrarily chosen number such as the age of 65. This measure is called years of potential life lost (YPLL).
Primary energy	Energy embodied in natural resources (such as coal, crude oil, sunlight or uranium) that has not undergone any ***anthropogenic*** conversion or transformation.
Primary productivity	The transformation of chemical or solar energy to ***biomass***. Most primary production occurs through photosynthesis, through which green plants convert solar energy, CO_2, and water to glucose and eventually to plant tissue. In addition, some bacteria in the deep sea can convert chemical energy to ***biomass*** through chemosynthesis.
Primary wastewater treatment	In the primary stage of ***wastewater treatment***, sewage flows through large tanks which are used to settle sludge while grease and oils rise to the surface and are skimmed off. Tanks are usually equipped with mechanically driven scrapers that continually drive the collected sludge towards a hopper in the base of the tank where it is pumped to sludge treatment facilities.
Projection	The act of attempting to produce a description of the future subject to assumptions about certain preconditions, or the description itself, such as "assuming it is 30°C tomorrow, we will go to the beach".
Purchasing power parity (PPP)	The number of currency units required to purchase the amount of goods and services equivalent to what can be bought with one unit of the currency of the base country, for example, the US dollar.
Radiative (or climate) forcing (RF)	Radiative forcing is the change in the net vertical irradiance, expressed in watts per square metre (W/m^2), at the tropopause due to an internal change or a change in the external forcing of the climate system, such as, for example, a change in the concentration of CO_2 or the output of the sun. The measurement of the capacity of a gas or other forcing agents to affect that energy balance, thereby contributing to ***climate change***. Radiative forcing expresses the change in energy in the atmosphere due to ***greenhouse gas*** emissions. The RF of a gas is defined as the difference between incoming solar radiation and outgoing infrared radiation caused by the increased concentration of that gas. A positive radiative forcing tends to warm the surface and a negative radiative forcing tends to cool the surface. The radiative forcing is normally quoted as a global and annual mean value.
Reference scenario	See ***Baseline scenario***.
Renewable energy	Energy that is collected from renewable resources which does not rely on finite stocks of fuels and are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves and geothermal heat. Renewable energy often provides energy in four important areas: electricity generation, air and water heating/cooling, transportation and rural (off-grid) energy services.

Term	Definition
Residence time	Residence time (also known as removal time) is the average amount of time that a particle spends in a particular system.
Sanitary or engineered landfill	A sanitary landfill is a land disposal site for waste, which is designed to protect from environmental pollution and health risks. It is the opposite of an open dump. Landfills are built to concentrate the waste in compacted layers to reduce the volume and monitored for the control of liquid and gaseous ***effluent*** in order to protect the environment and human health. It is an engineered pit, in which layers of solid waste are filled, compacted and covered for final disposal. It is lined at the bottom to prevent ***groundwater*** pollution. Engineered landfills consist of a lined bottom; a leachate collection and treatment system; ***groundwater*** monitoring; gas extraction (the gas is flared or used for energy production); and a cap system. The capacity is planned and the site is chosen based on an environmental risk assessment study (UNEP 2002). Landfills need expert design as well as skilled operators and proper management to guarantee their functionality.
Scenario	A description of how the future may unfold based on “if-then” propositions, typically consisting of a representation of an initial ***baseline*** situation, a description of the key drivers and changes that lead to a particular future state. For example, “given that we are on holiday at the coast, if it is 30ºC tomorrow, we will go to the beach”.
Secondary pollutants/ particles	***Pollutants*** that are not directly emitted as such, but form when other ***pollutants*** (primary ***pollutants***) react in the ***atmosphere***. Particles that are formed in the ***atmosphere***. Secondary particles are products of the chemical reactions between gases, such as NO_x, sulphur oxides, ammonia, and organic products.
Secondary wastewater treatment	Secondary ***wastewater treatment*** is a biological treatment process to remove biodegradable dissolved and colloidal organic matter using aerobic biological treatment processes. Secondary treatment follows ***primary treatment***.
Security	Relates to personal and environmental security. It includes access to natural and other resources and freedom from violence, crime and war, as well as security from natural and human-caused disasters.
Shale gas	Shale gas refers to natural gas that is trapped within shale formations. Shales are fine-grained sedimentary rocks that can be rich sources of petroleum and natural gas.
Short lived climate pollutants (SLCPs)	Short-lived climate ***pollutants*** are defined as gases and particles that contribute to warming and that have a lifetime from a few days to approximately 10 years. These include ***black carbon (BC), tropospheric ozone (O_3)*** and its ***precursors*** CO, NMVOC and NO_x, CH_4, and some ***HFCs***. Short-lived climate ***pollutants*** are powerful climate forcers that remain in the ***atmosphere*** for a much shorter period of time than CO_2, yet their potential to warm the ***atmosphere*** can be many times greater. Certain short-lived climate ***pollutants*** are also dangerous air ***pollutants*** that have harmful effects for people, ***ecosystems*** and agricultural productivity.

Term	Definition
Sociodemographic index	A summary measure of a geography's socio-demographic development. The index i is based on average income per person, educational attainment and total fertility rate (TFR). A sociodemographic index (SDI) contains an interpretable scale: zero represents the lowest income per person, lowest educational attainment and highest TFR observed across all ***GBD*** geographies. The estimates were developed by ***GBD*** researchers.
Solid fuel	Refers to various types of solid material that are used as fuel to produce energy and provide heating. Solid fuels include wood, charcoal, peat, coal, hexamine fuel tablets, and pellets made from wood, corn, wheat, rye and other grains.
Source apportionment	A practice of deriving information about pollution sources and the amount they contribute to ambient air pollution levels. This task can be accomplished using three main approaches: emission inventories, source-oriented models and receptor oriented models.
Species (chemical)	A set of chemically identical atomic or molecular structural units in a solid array. Species can be the molecular fragments, ions, atoms and molecules that can explore the same set of molecular energy levels on a defined time scale or being subjected to a chemical process or to a measurement.
Stomata	Pores found in the leaf and stem of the plant epidermis that are used for gas exchange.
Stomatal conductance	A numerical measure of the rate of passage of either water vapour or carbon dioxide through the stomata of a plant.
Stratospheric ozone	Region of the ***atmosphere*** between the ***troposphere*** and mesosphere, having a lower boundary of approximately 9 kilometres at the poles to 16 kilometres at the equator and an upper boundary of approximately 50 kilometres. Depending upon latitude and season, the temperature in the lower stratosphere can increase, be isothermal, or even decrease with altitude, but the temperature in the upper stratosphere generally increases with height due to ***absorption*** of solar radiation by O_3.
Sulphate aerosols	***Particulate matter*** that consists of compounds of sulphur (S) formed by the interaction of SO_2 and sulphur trioxide (SO_3) with other compounds in the ***atmosphere***. Sulphate ***aerosols*** are injected into the ***atmosphere*** from the combustion of ***fossil fuel*** and the eruption of volcanoes like Mt. Pinatubo. Recent theory suggests that sulphate ***aerosols*** may lower the Earth's temperature by reflecting away solar radiation (negative ***radiative forcing***).
Sustainability	A characteristic or state whereby the needs of the present and local population can be met without compromising the ability of future generations or populations in other locations to meet their needs.
Sustainable development	Development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs.

Term	Definition
Sustainable Development Goals	The Sustainable Development Goals (SDGs) are an intergovernmental set of development goals. All United Nations members have committed to work towards the achievement of all the goals by their target date 2030. The SDGs are made up of 17 goals and 169 indicators. The SDGs have replaced the Millennium Development Goals.
Synergies	These arise when two or more processes interact in such a way that the outcome is greater than the sum of their separate effects (e.g. multiplicative rather than additive).
Technology	Physical artefacts or the bodies of knowledge of which they are an expression. Examples are ***renewable-energy*** technologies and waste-to-energy technology. Technology and ***institutions*** are related. Any technology has a set of practices, rules and regulations surrounding its use, access, distribution and management.
Terrestrial ecosystems	A terrestrial ***ecosystem*** is a type of ***ecosystem*** found only on land masses. Six primary terrestrial ***ecosystems*** exist: tundra, taiga, temperate deciduous forest, tropical rain forest, grassland and desert. The biotic or living things found in an ***ecosystem***, include various life forms, such as plants and animals. The abiotic or non-living things found in an ***ecosystem***, include the various land forms and the climate.
Tertiary wastewater treatment	The purpose of tertiary ***wastewater treatment*** is to provide a final treatment stage to raise the ***effluent*** quality before it is discharged to the receiving environment (sea, river, lake, ground, etc.).
Time-series study/analysis (short term)	Time-series studies are routinely used to estimate associations between adverse health outcomes and short-term exposures to ambient air ***pollutants***. The Poisson log-linear model with the assumption of constant over-dispersion is the most common approach, particularly when estimating associations between daily air pollution concentrations and aggregated counts of adverse health events throughout a geographical region.
Third pole area	The Third Pole contains the world's highest mountains, including all 14 peaks above 8,000 metres, is the source of 10 major rivers, and forms a formidable global ecological buffer. It covers the Hindu Kush-Himalayan region with an area of more than 4.3 million square kilometres in Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan. This region stores more snow and ice than anywhere else in the world outside the polar regions, giving its name: the Third Pole.
Transboundary pollution	The pollution that originates in one country but, by crossing the border through ***pathways*** of water or air, is able to cause damage to the environment in another country.
Troposphere	The lowest part of the ***atmosphere*** from the Earth's surface to about 10 kilometres in altitude in midlatitudes (ranging from 9 kilometres to 16 kilometres in high latitudes in the tropics on average) where clouds

Term	**Definition**
	and weather phenomena occur. In the troposphere temperatures generally decrease with height.
Urbanization	An increase in the proportion of the population living in urban areas.
Volatile organic compounds (VOCs)	Organic chemical compounds that under normal conditions are gaseous or can vaporize and enter the atmosphere. VOCs include such compounds as CH_4, benzene, xylene, propane and butane. CH_4 is primarily emitted from agriculture (from ruminants and cultivation), whereas non-CH_4 VOCs (or NMVOCs) are mainly emitted from transportation, industrial processes and use of organic solvents. Organic chemical compounds that have high enough vapour pressures under normal conditions to significantly vaporize and enter the atmosphere include ***hydrocarbons*** (CxHy) but also other organic chemicals that can be emitted from a very wide range of sources, including ***fossil fuel*** combustion, industrial activities, and natural emissions from vegetation and fires. Some ***anthropogenic*** VOCs such as benzene are known carcinogens. VOCs are also of interest as chemical ***precursors*** of ground-level ***O_3*** and ***aerosols***. The importance of VOCs as ***precursors*** depends on their chemical structure and atmospheric lifetime, which can vary considerably from compound to compound. Large VOCs oxidize in the atmosphere to produce nonvolatile chemicals that condense to form ***aerosols***. Short-lived VOCs interact with NO_x to produce high ground-level O_3 in polluted environments. CH_4, the simplest and most long-lived VOC, is of importance both as a ***greenhouse gas*** and as a source of background tropospheric ozone.
Vulnerable people	The groups and communities at a higher risk for poor health as a result of the barriers they experience to social, economic, political and environmental resources, as well as limitations due to illness or disability.
Waste heat recovery	The process of harnessing the heat generated by power plants or industrial machinery, which would otherwise remain unused, in order to alleviate demands on energy generation. This reduces the total amount of fuel needed.
Wastewater treatment	Any of the mechanical, biological or chemical processes used to modify the quality of wastewater in order to reduce pollution levels.
World Health Organization (WHO) air quality guideline	A document developed by the WHO containing recommendations for clinical practice or public health ***policy***. WHO air quality guidelines, which are designed to offer guidance in reducing the health impacts of air pollution, are based on expert evaluation of current scientific evidence.
World Health Organization (WHO) Interim Target	A level of pollution higher than that set by the ***WHO air quality guideline***, established as an interim target to assist implementing agencies to make progress towards meeting the guideline levels. The interim targets are given for each air ***pollutant***. These targets aim to promote a shift from high air ***pollutant*** concentrations, which have acute and serious health consequences, to lower ones. If these targets were to be achieved, one could expect significant reductions in risks for acute and ***chronic*** health effects from air pollution.

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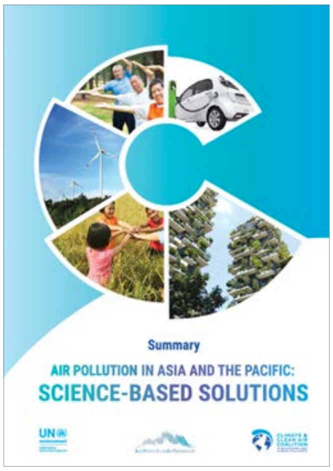
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