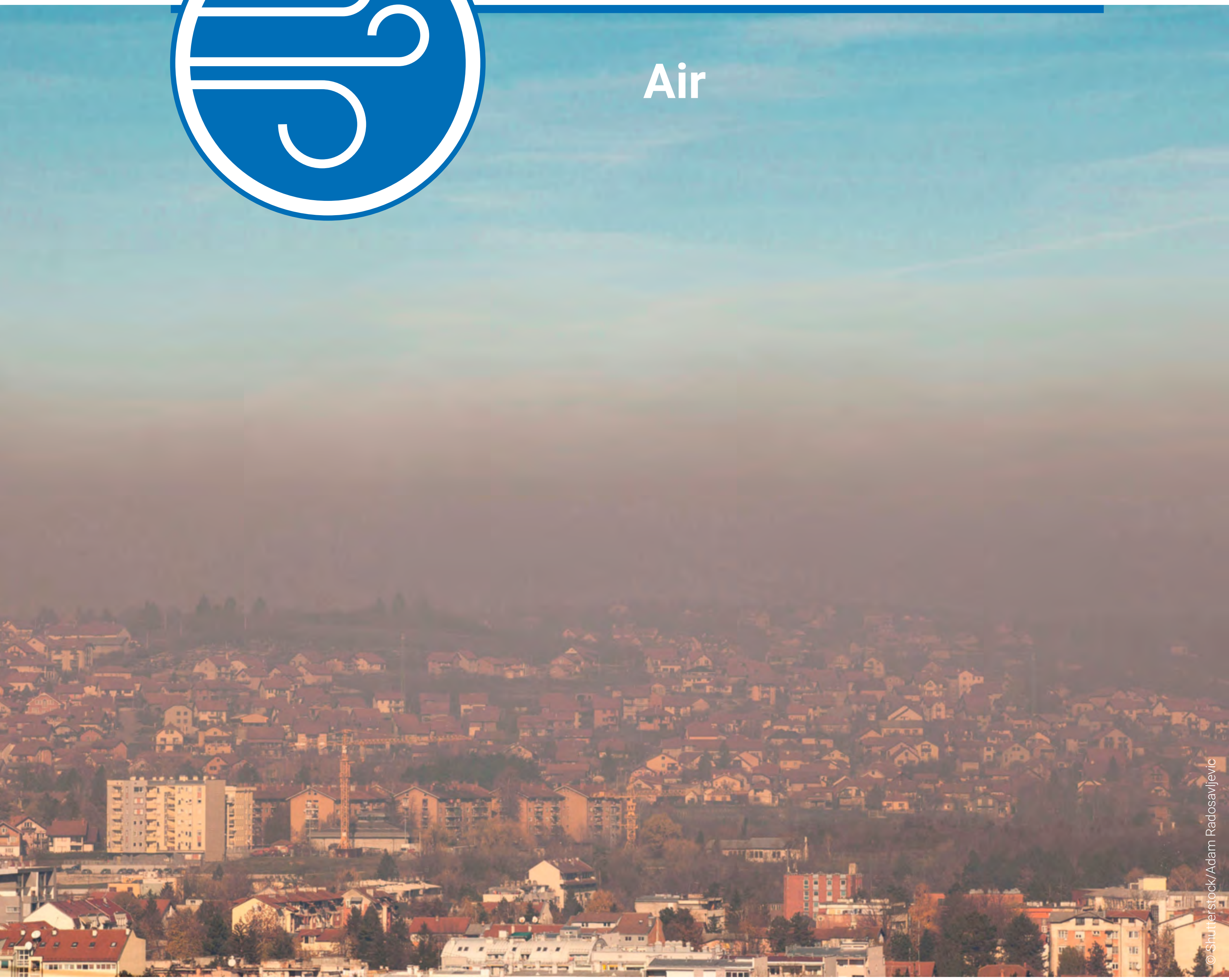
Chapter 5

Air



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Executive summary

Concentrations of CO_2 and other long-lived greenhouse gases (GHGs) continue to increase, driven mainly by people consuming fossil fuels to satisfy ever-increasing demands for energy (*well established*). {5.2.4}

Given the current concentrations of GHGs and their lifetime in the atmosphere, significant changes in climate and sea levels are unavoidable, with widespread consequences for people and the environment (*well established*). There is robust evidence that climate change and increased climate variability worsen existing poverty, exacerbate inequalities and trigger new vulnerabilities. However, even greater changes are expected in the future if action is not taken soon to halt GHG emissions. {5.3.4}

Climate change impacts include increased frequency and magnitude of heatwaves and storms (*established but incomplete*); changes in the distribution of disease vectors, exacerbation of air pollution episodes, and decreases in water supply and impacts on crop yields and food prices. {5.3.4}

Efforts to decrease emissions of short-lived climate pollutants (SLCP), specifically black carbon (BC), methane (CH_4), tropospheric ozone (O_3) and hydrofluorocarbons (HFCs), are a critical component of an integrated climate change mitigation and air quality management programme (*well established*). Along with rapid mitigation of long-lived GHG emissions, decreases in SLCP emissions achieve the objectives of the United Nations Framework Convention on Climate Change (UNFCCC). {5.2.4}

Air pollution is the most important environmental contributor to the global burden of disease, leading to an estimated 6 million to 7 million premature deaths annually and large economic losses (*established but incomplete*). Of those deaths, 2.6 million to 3.8 million deaths have been attributed to burning wood, coal, crop residue, dung and kerosene for cooking, heating and lighting. Another 3.2 million to 3.5 million deaths have been attributed to other sources of ambient air pollution. The monetary value of the global welfare losses has been estimated at US$5.1 trillion (or 6.6 per cent of global world product). {5.3.1}

People who are elderly, very young, sick and poor are more susceptible to air pollution, which can exacerbate pre-existing illnesses or conditions (*well established*). Exposures are highest for people living in urban areas in low- and middle-income countries and for the approximately 3 billion people who depend on burning solid fuels or kerosene to meet household energy needs. {5.3.1}

Globally, decreasing emission trends in some sectors and regions have been offset by increasing emission trends in rapidly developing and emerging economies and areas of rapid urbanization (*well established*). {5.2}

East and South Asia have the highest total number of deaths attributable to air pollution, due to large populations and cities with high levels of pollution (*well established*). These regions also bear the largest health burden caused by the production of goods consumed in other regions of the world, primarily Western Europe and North America. {5.3.1}

As controls have been placed on power plants, large industrial facilities and vehicles, the relative contributions of other sources have grown in importance *(well established).* Sources of pollution that are increasingly relevant to achieving air quality objectives include agriculture, domestic fuel burning, construction and other portable equipment, artisanal manufacturing and fires. The relative contributions of these sources to air quality problems differs from region to region, such that priorities for air pollution control may vary in different locations. {5.2.1}

Emissions of ozone-depleting substances (ODSs) have decreased dramatically as a result of the Montreal Protocol (*well established*). New studies provide robust evidence that stratospheric ozone over Antarctica has started to recover. Although stratospheric ozone concentrations in other regions have increased since 2000, the expected increase in total atmospheric column ozone and decrease in ultraviolet (UV) radiation reaching the Earth's surface have not been observed outside Antarctica due to natural variability, increases in GHGs, and changes in attenuation of the UV radiation by tropospheric ozone, clouds and aerosols. {5.2.3}

International agreements have been successful in addressing specific chemicals, but new chemical risks are emerging (*established but incomplete*). Environmental concentrations of persistent organic pollutants (POPs) have been reduced in Europe, North America, Asia and the Pacific, and the Arctic. {5.2.2}

Rapid development and urbanization combined with insufficient environmental governance in many regions suggest that climate change and air pollution are likely to worsen before they improve without additional policy interventions *(well established).* However, future policy efforts can build upon renewed attention to these issues in international forums and several decades of experience with various governance strategies in different countries. {5.4}

5.1 Introduction

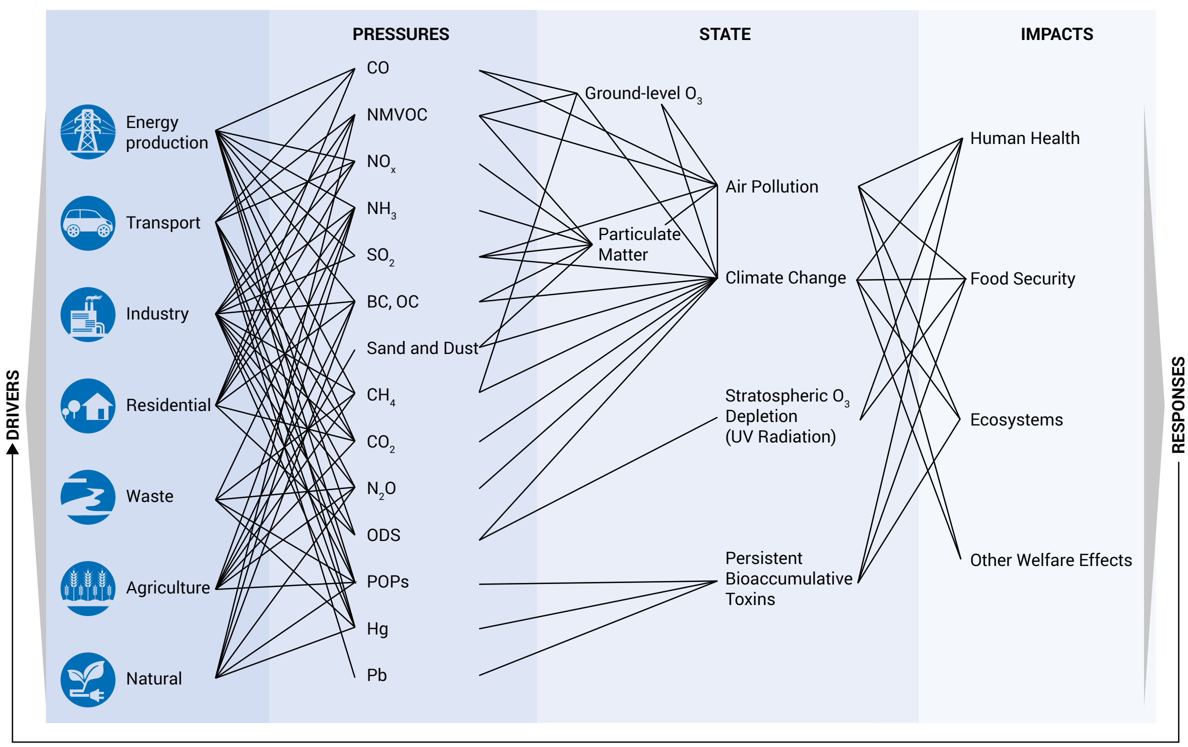
Emissions generated by human activity have changed the composition of the Earth's atmosphere, with consequences for the health of people and the planet. The impacts of human activity on the atmosphere are often framed in terms of four separate challenges: air pollution; climate change; stratospheric ozone depletion; and persistent, bioaccumulative, toxic substances (PBT) (Abelkop, Graham and Royer 2017). The causes of these four challenges, their effects on atmospheric composition and meteorological processes, and their impacts on humans and ecosystems are closely intertwined **(see Figure 5.1)**. Solutions to these challenges are also interrelated, as changes in lifestyle, technology and policy alter emissions of multiple pollutants simultaneously with a variety of interrelated implications. This chapter describes these four challenges together following the Drivers, Pressures, State, Impact, Response (DPSIR) framework (see Section 1.6).

Since the fifth Global Environment Outlook (GEO-5) was published in 2012, a number of developments have focused international attention on changing atmospheric composition. Estimates of the global burden of disease contributed by air pollution have doubled (comparing assessments published in 2004, 2012 and 2017) primarily due to new exposure estimates informed by satellite-borne instruments (Lim *et al.* 2012; Cohen *et al.* 2017). The United Nations Environment Assembly of the United Nations Environment Programme (UNEA) (2014; 2017) and World Health Assembly of the World Health Organization (WHO) (2015) have responded with resolutions to encourage national-level actions to address air pollution. Concentrations of major GHGs are still growing strongly (World Meteorological Organization [WMO] 2017a) and indicators of climate change

Table 5.1: Some atmospheric chemical components

BC	black carbon
CFCs	chlorofluorocarbons
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
GHGs	greenhouse gases
HCFCs	hydrochlorofluorocarbons
HFCs	hydrofluorocarbons
Hg	mercury
N_2O	nitrous oxide
NH_3	ammonia
NMVOC	non-methane volatile organic compounds
NO	nitrogen oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
O_3	ozone, tropospheric and stratospheric
OC	organic carbon
ODS	ozone-depleting substances
PAHs	polycyclic aromatic hydrocarbons
Pb	lead
PBDE	polybrominated diphenyl ethers
PBTs	persistent, bioaccumulative, toxic chemicals (includes POPs, metals)
PCB	polychlorinated biphenyl
PFAS	per- and polyfluoroalkyl substances
PM	particulate matter
PM_{10}	PM less than 10 µm in diameter
$PM_{2.5}$	PM less than 2.5 µm in diameter
POPs	persistent organic pollutants (as defined by international agreements)
SO_2	sulphur dioxide

Figure 5.1: Primary linkages between pressures, state and impacts of atmospheric change



This figure is intended as a road map for the reader, showing the relationships between the main topics and pollutants discussed in this chapter. Chemical symbols and abbreviations are defined in Table 5.1.

have continued to accumulate. Targets in the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) expired but were replaced by new ones under the Doha Amendment and new commitments under the Paris Agreement (UNFCCC 2016). Complementing the work of the UNFCCC, new efforts have targeted reductions of short-lived climate pollutants (SLCPs) from specific sectors with benefits for climate change mitigation and human health (Climate and Clean Air Coalition [CCAC] 2015). As stratospheric ozone (O_3) has continued its recovery, the Kigali Amendment to the Montreal Protocol (United Nations 2016a) has harnessed this successful international agreement to help mitigate the climate impacts of hydrofluorocarbons (HFCs), originally introduced as substitutes for ozone-depleting substances (ODS). Emissions of mercury (Hg) have declined in some regions and increased in others. Emissions of some banned persistent organic pollutants (POPs) have declined due to the implementation of international agreements. However, atmospheric burdens of other POPs and PBTs remain at levels of concern, and new chemical risks have been identified (United Nations Environment Programme [UNEP] 2017a).

Efforts to achieve each of the Sustainable Development Goals (SDGs) are linked directly or indirectly to mitigating air emissions and changes to atmospheric composition, as shown in **Figure 5.2**.

In the GEO-6 regional assessments, air pollution, climate change and energy development, as well as the intersection of these three issues, were identified as top priorities in every region. Growing cities, energy, and transportation demand were consistently identified as issues of concern. Indoor air pollution and access to clean household energy were priorities in Africa and Asia. Other regional priorities highlight differences in the institutional capacities of governments in different regions: improving observational networks (Africa, Latin America and the Caribbean, West Asia), strengthening governance (Asia, Latin America and the Caribbean), and understanding costs and benefits of mitigation measures (Asia). The following sections build upon the GEO-6 regional assessments to explore the state of these challenges from a global perspective.

5.2 Pressures: emissions

People alter the atmosphere primarily by generating emissions. Trends in human-caused emissions are driven by changes in population, urbanization, economic activity, technology and climate ('the drivers'), as well as by behavioural choices, including lifestyle, and conflict. In turn, these drivers are influenced by policies ('responses'). Natural emission sources, including emissions from vegetation, soils, wildfires, and windblown sand and dust, also contribute to emissions, but can be affected by people (e.g. through land-use change).

Although an increasing amount of emissions information in some GEO regions is publicly available, there is no global reporting programme applicable to all sources and pollutants and no comprehensive emissions data repository. The Aarhus Convention and its Protocol on Pollutant Release and Transfer Registers (PRTR) aspires to establish a global network, building on the work of the United Nations Economic Commission for Europe (UNECE) and the Organisation for Economic Co-operation and Development (OECD) (see http://prtr.net). Currently, compiling a consistent global emissions inventory requires research effort. This assessment uses the latest anthropogenic emissions data developed using the Community Emissions Data System (CEDS), an open source, global emissions inventory data system that was developed

Figure 5.2: Linkages between changes in atmospheric composition and achievement of the Sustainable Development Goals

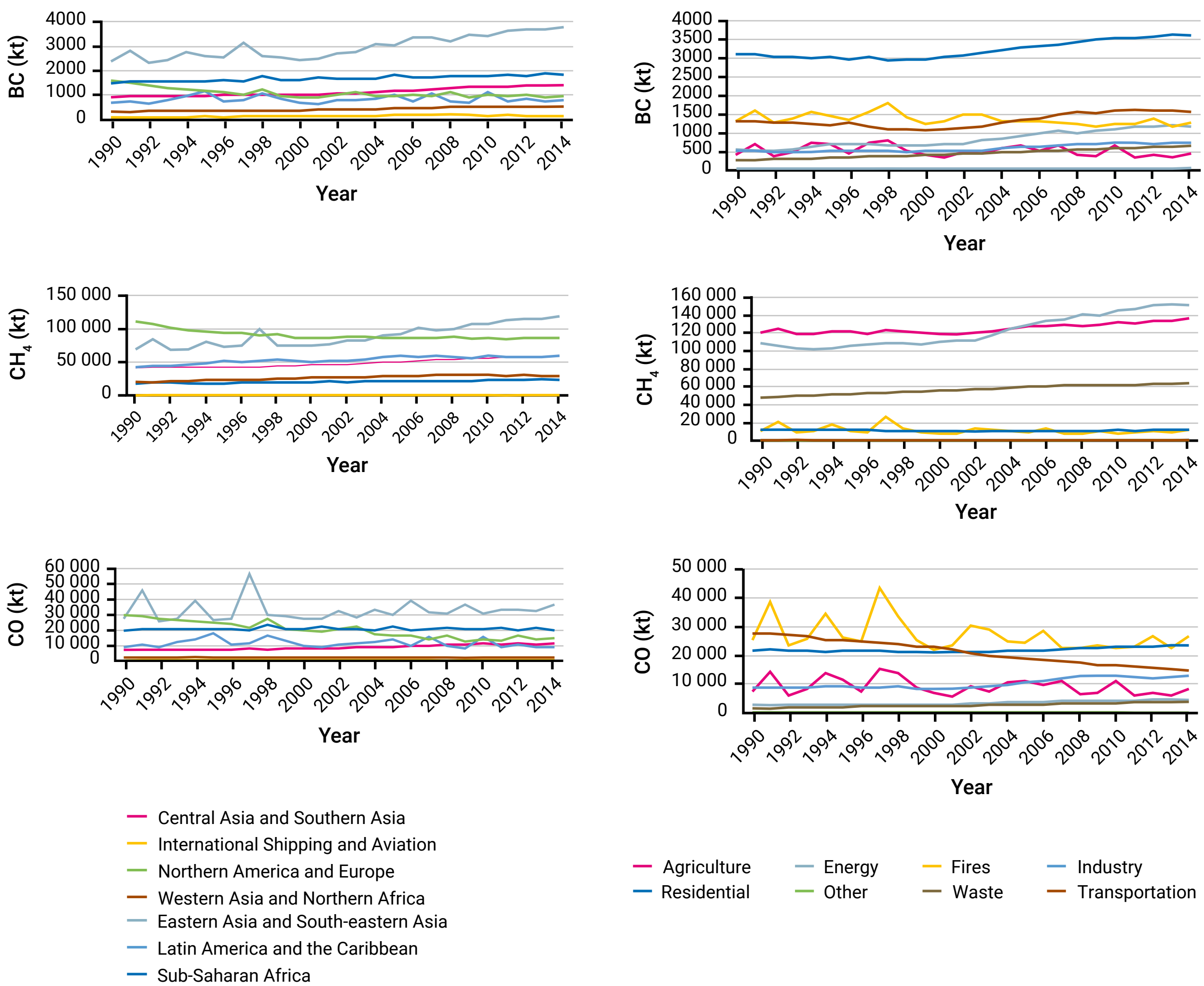
Direct linkages are shown with bold arrows, indirect linkages with light arrows.

to provide consistent long-term emission trends for use in global atmospheric modelling efforts, such as those supporting the preparation of Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report (Hoesly *et al.* 2018). Open biomass burning emissions, whether anthropogenic or natural, are drawn from a separate inventory created for global modelling efforts by merging information from satellite-based estimates, sedimentary charcoal records, historical visibility records and multiple fire models (van Marle *et al.* 2017). Together, these data sets provide an up-to-date and consistent basis to examine trends for most air pollutants and greenhouse gases (GHGs) **(see Figure 5.3)**.

Globally, anthropogenic carbon dioxide (CO_2) emissions increased by more than 40 per cent over the period 1990-2014, driven by large increases in Asia and counteracted by small declines in North America and Europe. Sulphur dioxide (SO_2) emissions are the only ones to have declined globally during this period, with increases of more than 50 per cent in Asia offset by a more than 75 per cent decrease in North America and Europe. In recent years, emissions of SO_2 and nitrogen oxides (NO_X) have begun to decline in East Asia. The inclusion of wild and agricultural fires significantly increases the inter-annual variability of emissions of non-methane volatile organic compounds (NMVOC), carbon monoxide (CO), black carbon (BC) and organic carbon (OC).

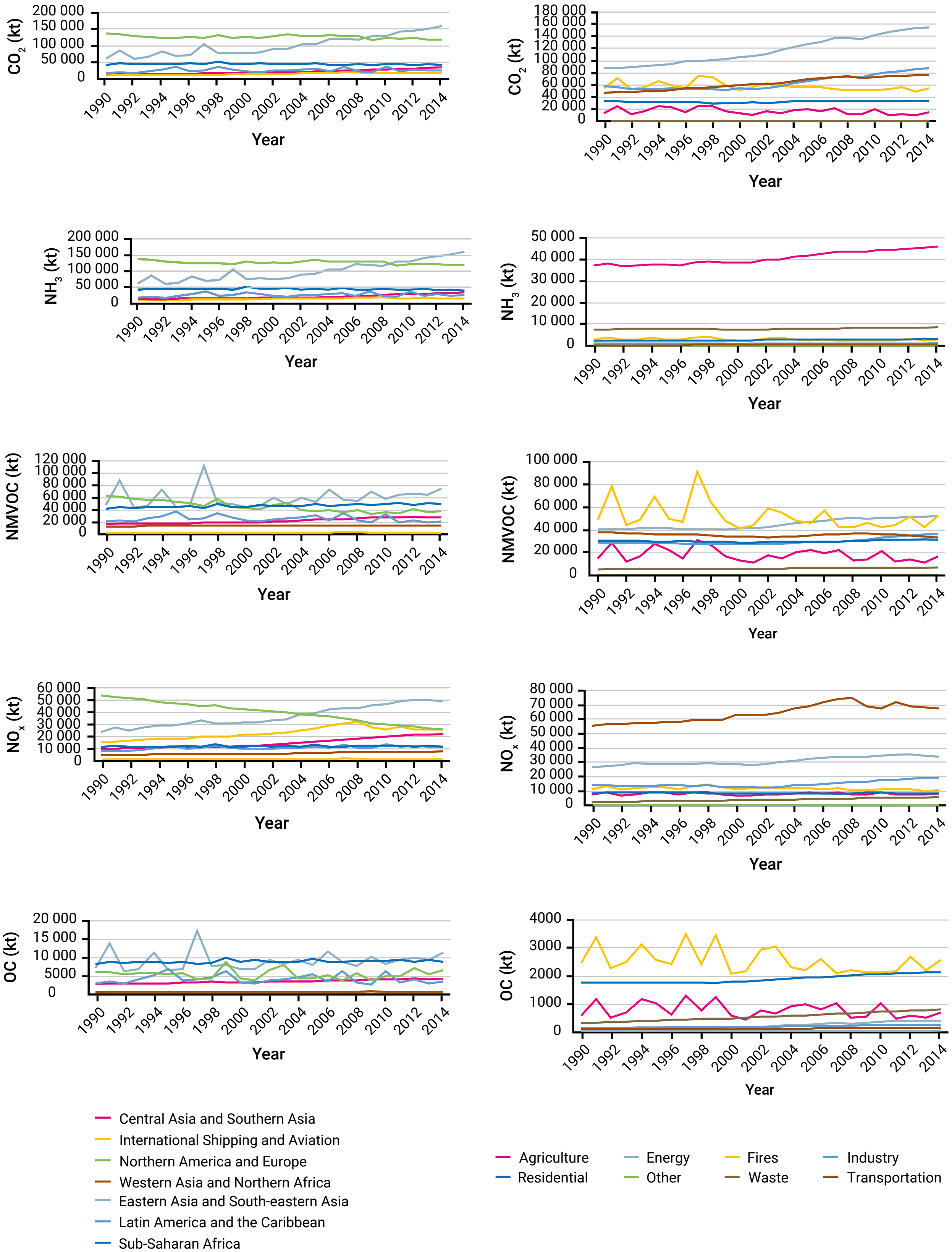
The emissions data presented here are best estimates with different degrees of uncertainty depending on pollutant, sector, region and time period. Hoesly *et al.* (2018) found that CEDS estimates are slightly higher than previous global inventories (e.g. Lamarque *et al.* 2010; European Commission 2016). In general, estimates of CO_2 and SO_2 emissions have uncertainties on the order of ±10 per cent for a 5-95 per cent confidence interval, whereas BC and OC emissions have uncertainties on the order of a factor of two. Uncertainties for CO, NO_X, NMVOC and ammonia (NH_3) emissions lie in between these two endpoints (Hoesly *et al.* 2018). Uncertainty also varies by sector: emissions from large electricity generation plants are well characterized, whereas emissions generated by military conflicts are not well understood or commonly included in inventories.

Figure 5.3: Annual emission trends from 1990 to 2014 in kilotons by pollutant, region and sector



Source: Hoesly *et al.* (2018).

Figure 5.3 (continued): Annual emission trends from 1990 to 2014 in kilotons by pollutant, region and sector



Source: Hoesly *et al.* (2018).

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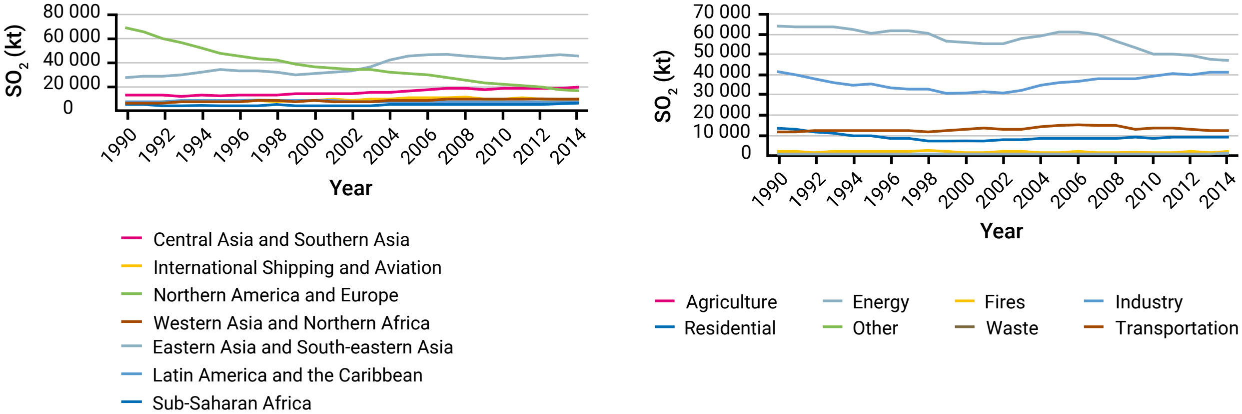
Figure 5.3 (continued): Annual emission trends from 1990 to 2014 in kilotons by pollutant, region and sector



Source: Hoesly *et al*. (2018).

There are considerable gaps in available emissions data for POPs, which include pesticides, industrial chemicals and products of incomplete combustion or chemical reactions. Available data in Europe, America and Central Asia indicate that emissions decreased significantly between 1990 and 2012 for the most studied POPs, due to regulations, including the Stockholm Convention (UNEP 2014a; UNEP 2014b; UNEP 2015a; UNEP 2015b). Nevertheless, alongside the growing number of listed POPs and candidate substances, unregulated POPs emissions may be increasing. Many commercial products contain unknown quantities and types of unregulated POPs, often with unknown effects (see also Section 4.3.3).

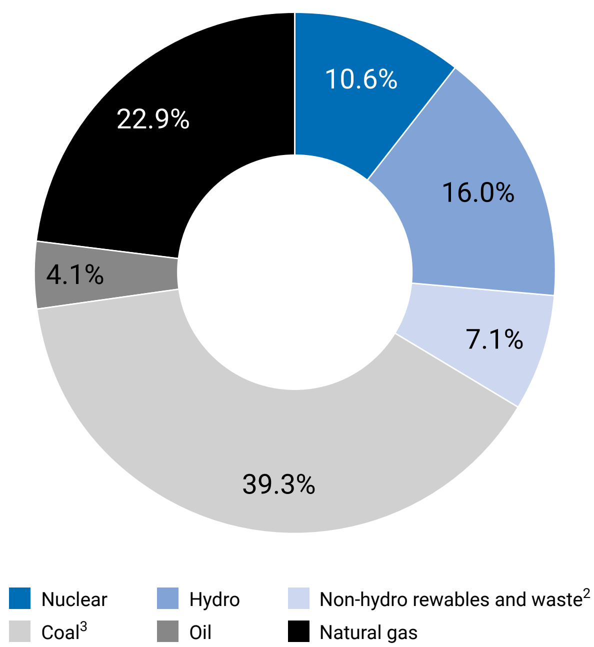
The UNEP Global Mercury Assessment estimated that anthropogenic Hg emissions to air were 2,220 (2,000-2,820) (metric) tons/year for 2015 (UNEP 2013a). Globally, artisanal and small-scale gold mining (ASGM) was responsible for about 38 per cent of total anthropogenic Hg emissions to air in 2015, followed by coal combustion (about 21 per cent), non-ferrous metal production (about 15 per cent) and cement production (about 11 per cent). Asia is the main source region, contributing about 49 per cent of 2015 global anthropogenic Hg emissions, followed by South America (18 per cent) and sub-Saharan Africa (16 per cent). Current anthropogenic sources contribute about 30 per cent of annual Hg emissions to air, while natural geological sources contribute about 10 per cent. The remaining 60 per cent comes from 're-emissions' of previously released Hg from soils and oceans, mostly from anthropogenic sources (UNEP 2013a).

Globally, both the production and consumption of ODS, and thus ODS emissions, declined by more than 99 per cent between 1990 and 2016 (UNEP 2017b). Chlorofluorocarbons (CFCs) and halons, the most potent ozone depleters, have been replaced by shorter-lived hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), although recent measurements suggest that new emissions of trichlorofluoromethane (CFC-11) may be occurring (Montzka *et al.* 2018). The less-depleting HCFCs are now being phased out in favour of chemicals that do not contribute to ozone depletion. Concerns about the potential future contribution of HFCs to climate change led to the 2016 Kigali Amendment to the Montreal Protocol, which will limit future HFC emissions.

5.2.1 Electricity and fuel production

The electricity and fuel production sector (labelled 'energy' in **Figure 5.3**) is the largest anthropogenic emitting sector of CO_2, methane (CH_4), SO_2 and NMVOC, and the main emitting sector of other air pollutants. Within the sector, electricity generation contributed around 70 per cent of CO_2, 71 per cent of SO_2 and 72 per cent of NO_x in 2014 (Hoesly *et al.* 2018).

Figure 5.4: Global fuel shares of electricity generation in 2015[1]



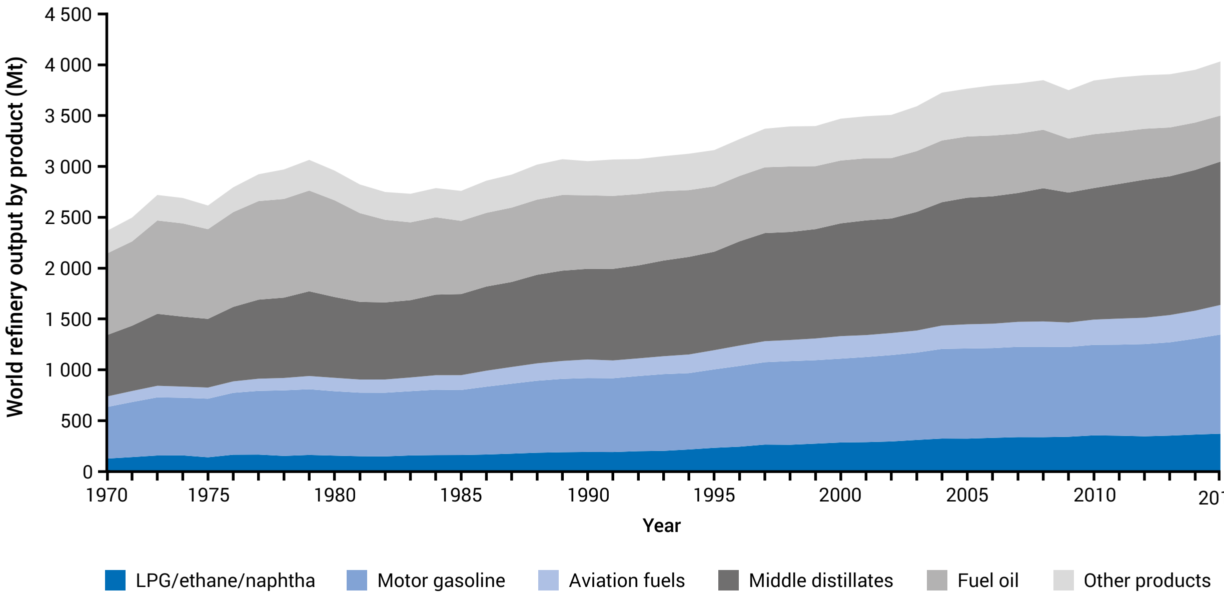
Notes: [1] Excludes electricity generation from pumped storage. [2] Includes geothermal, solar, wind, heat, etc. [3] Peat and oil shale are aggregated with coal.

Source: IEA (2017).

Despite increases in renewable energy capacity, fossil fuels still dominate the global power system (see **Figure 5.5**). Three-quarters of the sector's SO_2 emissions, 70 per cent of its NO_X emissions and over 90 per cent of those of primary particulate matter less than 2.5 μm in diameter ($PM_{2.5}$) are from coal-fired plants. Coal combustion is also the second most important anthropogenic source of global Hg emissions (International Energy Agency [IEA] 2016a). In 2015, gas-fired generation emitted close to 20 per cent of NO_X from power generation, but barely any SO_2 or primary $PM_{2.5}$ (IEA 2016a).

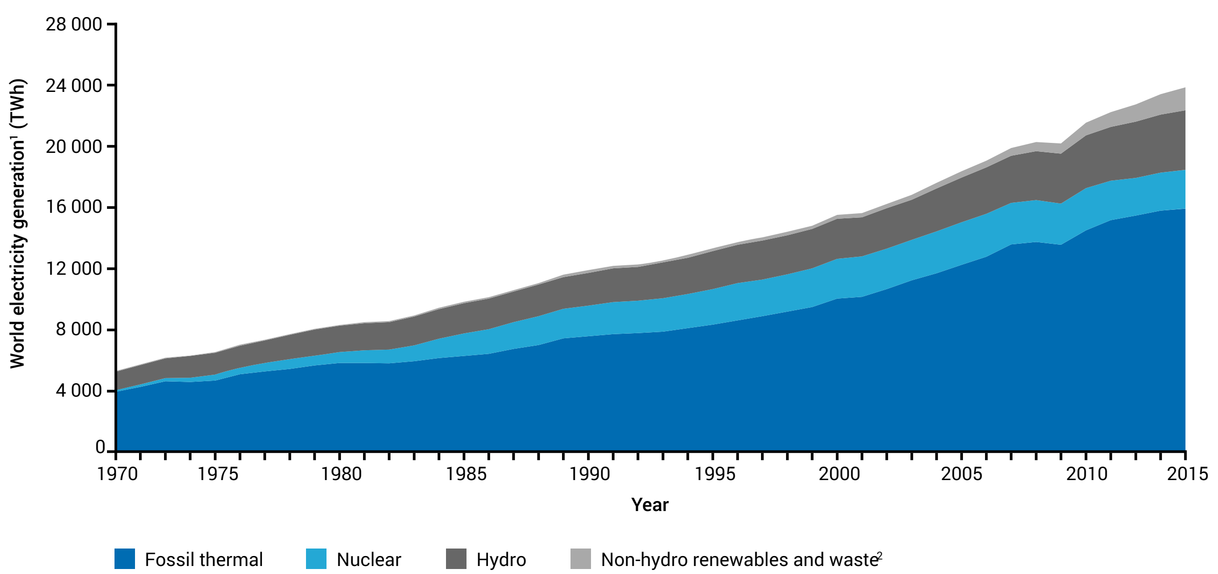
From 1990 to 2015, global petroleum fuel production saw slow but sustained growth (see **Figure 5.5**). CH_4 and NMVOC emissions from fuel production showed a corresponding increase (**Figure 5.3**). However, for electricity generation, production doubled between 1990 and 2015 (**Figure 5.6**),

Figure 5.5: World petroleum refinery output by-product (million tons)



Source: IEA (2017).

Figure 5.6: World electricity generation by fuel (terawatt hours)[1]



Notes: [1] Excludes electricity generation from pumped storage. [2] Other = geothermal, solar, wind, tide, wave, ocean, biofuels, heat, etc.
Source: IEA (2017).

but emissions of air pollutants did not increase at the same rate. Most importantly, SO_2 emissions from electricity generation declined after 2006 (see **Figure 5.3**). The main reasons for this decoupling include:

1. improvement of energy efficiency;
2. tighter emission standards for power plants and progress of end-of-pipe control technologies;
3. development of natural gas, renewable and nuclear power (Renewable Energy Policy Network for the 21st Century [REN21] 2016).

However, despite existing policies and the announced aims, targets and intentions, electricity demand is expected to increase by two-thirds by 2040 (IEA 2016b). Both end-of-pipe pollution control technologies and coal with low sulphur content may be used to achieve lower air pollutant emissions.

5.2.2 Transportation

In all regions of the world, the transportation of people and goods are significant sources of emissions of air pollutants, GHGs, ODS (from automobile air-conditioning units) and PBTs (including lead [Pb] and other metals). Road transport, including petrol- (gasoline-) and diesel-fuelled passenger cars and heavy-duty trucks, account for a dominant fraction of NO_x emissions, and a significant fraction of CO_2, CO, NMVOC and BC emissions (see **Figure 5.3**; Hoesly *et al.* 2018). Road traffic also contributes to emissions of primary PM from tyre and brake wear and entrained road dust (not included in **Figure 5.3**). Because cars and trucks operate and emit pollutants near where people live and work, they have a larger impact on air pollution exposures and associated health impacts than is proportional to their fraction of total emissions.

Total road transport activity is higher in North America and Europe than in other regions and is therefore responsible for greater CO_2 emissions, but those emissions have held steady for the last decade, with improvements in fuel efficiency keeping pace with increasing transport demand (Hoesly *et al.* 2018). The emissions of other transportation-related pollutants in North America and Europe have declined due to the introduction of vehicle emissions and fuel standards (see Section 12.2).

In developing countries, road transport emissions continue to rise as vehicle use is increasing faster than technological improvements, despite the introduction of emissions and fuel standards, which lag behind those in North America and Europe. Implementation of cleaner technologies is slowed by the trade in used vehicles from richer countries (UNECE and UNEP 2017). However, continued progress towards decreasing the sulphur content of fuel will enable the use of advanced emission control systems in all countries.

As emission standards are more widely applied to road vehicles, the relative fraction of emissions from non-road vehicles, such as heavy-duty construction equipment, is becoming increasingly important. Often running on diesel fuel, and with long lifetimes, such vehicles can be good candidates for retrofit control technologies or alternative fuels.

Maritime shipping is used to transport 80 per cent of global trade measured by volume (International Transport Forum 2017) and grew by more than 300 per cent between 1990 and 2015 when measured by ton-miles (United Nations Conference on Trade and Development [UNCTAD] 1997; UNCTAD 2017). Typically burning the heaviest petroleum products, ships are a significant source of SO_2 and CO_2 emissions globally and a source of SO_2, NO_x and BC emissions in coastal regions and port cities. Emission Control Areas have been established under international law (e.g. covering the North and Baltic seas and North American coastal waters) and national laws (e.g. covering Chinese ports and inland waters). The International Maritime Organization has announced new emission and fuel standards that are expected to dramatically decrease shipping emissions starting in 2020.

Aviation is a small but growing contributor to global emissions, accounting for less than about 2 per cent of global anthropogenic CO_2 emissions from fuel combustion (IEA 2017). Between 2000 and 2016, global air passenger travel increased 235 per cent (measured in passenger-km) and airfreight increased 174 per cent (measured in tons-km) (International Civil Aviation Organization [ICAO] 2016a). Aircraft emit pollutants directly into the upper atmosphere where their impact on ozone formation and climate forcing is larger than if emitted near the surface. The contribution of aviation CO_2 to radiative forcing is well quantified, but planes also emit water vapour, other gases and aerosols at high altitudes that trigger cloud formation and modify natural clouds and alter ozone and methane concentrations in the upper troposphere and lower stratosphere. The effects of these changes on climate forcing are not well quantified (Brasseur *et al.* 2016; Fahey *et al.* 2016). In 2016, the International Civil Aviation Organization (ICAO) adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), with a goal of capping the net CO_2 emissions from international aviation at 2020 levels (ICAO 2016b).

5.2.3 Industrial

Industry includes both manufacturing and mining sectors. The industrial sector emits air pollutants, GHGs, ODSs and PBTs, providing opportunities for multi-pollutant controls. Emissions and emission controls are often industry and process specific, or even regionally specific for some industries.

Nearly two-thirds of historic CO_2 and CH_4 emissions can be attributed to 90 investor- or government-owned businesses involved in the production of fossil fuels and cement (Heede 2014). Global emissions from industry increased for all pollutants between 1990 and 2014, except for SO_2 **(Figure 5.3)**, due to decreases in Europe's and North America's emissions being smaller than increases in other continents. Global SO_2 industrial emissions declined by 26 per cent from 1990 to 1999, due to the decrease in European and North American emissions, and increased after 1999, due to a considerable increase in China's (up to 2012 and reduced thereafter; Zheng *et al.* 2018) and other Asian countries' emissions (Hoesly *et al.* 2018).

The creation of many new industrial products, nanomaterials and chemicals poses a considerable challenge in terms of regulation and control. Their emissions are often neither regulated nor quantified, leading to unknown effects on the environment and health.

Technological innovation, technology transfer and tighter emission regulations to improve energy efficiency in manufacturing and mining sectors are key to reducing emissions. Examples include cleaner brick kiln technology, piloted in Asia and Latin America (Maithel *et al.* 2012; Center for Human Rights and Environment 2015); cleaner technologies and approaches to reduce or eliminate mercury use in ASGM piloted in several countries (United States Environmental Protection Agency [US EPA] 2018a); and Perform-Achieve-Trade schemes for energy intensive industry in India (Kumar and Agarwala 2013; Bhandari and Shrimali 2018).

5.2.4 Residential and commercial

Around 3.1 billion people, about 43 per cent of the global population in 2014, depend on burning fuels such as wood, crop residue, dung, coal and kerosene to cook their food and heat and light their homes (World Health Organization [WHO] 2016a). These fuels are the dominant source of BC and OC emissions globally and a major source of primary PM, polycyclic aromatic hydrocarbons (PAHs), CO and CO_2 emissions (Hoesly *et al.* 2018). Globally, exposure to residential smoke is one of the largest environmental health risk factors (Cohen *et al.* 2017). Lack of access to clean household energy is most severe in low- and middle-income countries, but the use of polluting fuels takes place in high-income countries and in urban as well as rural areas. Women and children are the most exposed to household air pollution, and also bear the greatest burden of gathering or procuring the fuels (WHO 2016b). Improving access to cleaner stoves and fuels (including wood pellets, liquid petroleum gas, natural gas, and sources of electricity) has been identified as a global priority, and although progress is being made, many challenges remain (Global Alliance for Clean Cookstoves 2014; WHO 2016a) (see Section 12.2.3).

The energy demands of the built environment (primarily the construction, heating, cooling, and lighting of residential and commercial buildings) account for a large fraction of GHG emissions in countries with developed economies and some cities in developing economies. Improving the energy efficiency of buildings and cities is necessary to meet global goals for GHG mitigation and to achieve co-benefits for air quality. These improvements require policy approaches such as building standards, labelling and rating systems, land-use planning, tax incentives, financing, voluntary commitments, awareness and education.

5.2.5 Waste management

While most developed countries have shifted towards cleaner and more efficient technologies for waste management, developing countries are still grappling with basic challenges in this area. Open dumping and burning of solid waste remain predominant in low-income countries and continues to be practised in many cities in lower-middle and upper-middle income countries. An estimated 2 billion people worldwide lack access to solid waste collection services, while 3 billion people lack access to adequate waste disposal facilities (UNEP and International Solid Waste Association 2015). Approximately 64 million people are directly affected by uncontrolled dumping and open burning at the world's 50 largest dumpsites, 42 of which are within 2 km of settlements (Waste Atlas Partnership 2014).

Open waste burning emits CO_2, CH_4, NMVOC and PM, and is a major source of POPs, including dioxins and furans, in many developing countries (UNEP 2014a; UNEP 2014b; UNEP 2015a; UNEP 2015b). In developed countries, the waste sector is also an important source of CH_4, metals and POPs. The illicit export of discarded electrical and electronic equipment (ewaste) from industrialized to developing countries (Rucevska *et al.* 2015) leads to significant emissions of POPs as well as other semivolatile organic contaminants (e.g. other halogenated flame retardants) in the informal e-waste receiving and processing areas (Breivik *et al.* 2016).

5.2.6 Agricultural and forestry

A broad array of agricultural and livestock farming practices alter the nitrogen cycle and GHG emissions, and increase pollution by fertilizers and pesticides, promoting biodiversity loss and soil degradation (DeLonge, Miles and Carlisle 2016). Agriculture, forestry and other land uses contribute 25 per cent to global GHG emissions (Seto *et al.* 2014). In developed countries, agriculture forms about 10 per cent of national GHG inventories (European Environment Agency 2017; US EPA 2017), while in developing countries the contribution is much higher.

Meat and dairy production, distribution and consumption have large environmental impacts on scales ranging from local to global (Leip *et al.* 2015). Industrial meat production and livestock operations are significant sources of GHGs, NH_3, dust and bioaerosols (Cole and McCoskey 2013). GHG emissions from livestock farming increased by 51 per cent globally between 1961 and 2010, mostly due to a 117 per cent increase in developing countries, moderated by a 23 per cent decrease in the developed countries (Caro *et al.* 2014; Pagano *et al.* 2017). Livestock production is responsible for 9 per cent of total GHG emissions (Caro *et al.* 2014). The largest source of these emissions (74 per cent) are dairy and beef cattle. N_2O and CH_4 emissions, which emanate from manure left on pasture, manure management and fermentation, increased by 57 per cent globally in the same period. However, rotational livestock grazing and other pasture management techniques are available to decrease the production of GHGs by the very same cattle, and at the same time preserve biodiversity (Nordborg and Röös 2016).

Along with livestock farming, fertilizer use results in significant emissions of NH_3, accounting for about 75 per cent of anthropogenic and about 60 per cent of total NH_3 emissions globally (Ciais *et al.* 2013) and contributing to regional PM formation and detrimental effects on terrestrial, freshwater
and marine ecosystems (Galloway *et al.* 2003).

Irrigation and fertilization practices for crops in general, as well as pasture management, can alter soil respiration rates, changing the amount of CO_2 emitted by soils to the atmosphere (UNEP 2017c). Pesticides used in agricultural applications are a major source of unregulated POPs into the environment and food chain, with various detrimental effects on health (see Section 4.3.4).

Biomass burning – including natural wildfires, prescribed burning of crop and forest residues, and prescribed burning of forests and savannah for land clearing – contributes significantly to air pollution by emitting CO, OC, BC, NO_x and NH_3, as well as GHGs, CO_2 and CH_4. Dominant types of biomass burned are savannah in Africa; boreal forest in the former Soviet Union, savannah and tropical forest in Latin America; and savannah, peat and tropical forest in eastern Asia. Biomass burning in South-East Asia, the drought triggered by the 2015-2016 El-Niño, coupled with anthropogenically induced deforestation over peat swamps and effects of previous widespread fires, have all led to severe regional air pollution events (Wooster, Perry and Zoumas 2012; Koplitz *et al.* 2016; Parker *et al.* 2016) (see Section 12.2.5).

5.2.7 Natural emissions and land-use change

Natural sources also contribute to emissions, but people have a strong influence on these in some regions through land-use change, especially cropland expansion (Pacifico *et al.* 2012; Ciais *et al.* 2013). Wind-blown dust from natural landscapes and unprotected cropland in arid and semi-arid regions is the largest source of atmospheric PM and the dominant fraction of coarse PM in many regions, such as northern Africa and the Middle East (Ginoux *et al.* 2012; Albani *et al.* 2014). Sustainable land and water management practices can decrease sand and dust storms, while contributing to reduced desertification, preserving biodiversity and mitigating climate change. Regional and national action plans, including those developed under the United Nations Convention to Combat Desertification (UNCCD), have the potential to address the underlying causes of sand and dust storms (UNEP, WMO and UNCCD 2016).

Globally, terrestrial vegetation is the dominant source of atmospheric NMVOCs, outweighing anthropogenic sources by a factor of ten (Guenther *et al.* 2012; Sindelarova *et al.* 2014). Biogenic NMVOCs tend to be highly reactive and can contribute significantly to O_3 and PM formation even in urban areas (Chameides *et al.* 1988). Soil microbial processes are an important part of the nitrogen cycle and can be a significant source of NO_x emissions outside urban areas and the dominant source of nitrous oxide (N_2O), a potent GHG, on a global basis (Ciais *et al.* 2013). Soil NO_x emissions are highest in croplands due to increased soil nitrogen content from fertilizer application (Vinken *et al.* 2014). Deforestation associated with expansion of croplands and pasturelands is estimated to have reduced global annual biogenic NMVOC emissions by 10-35 per cent and increased soil NO_x emissions by about 50 per cent since the 1850s, except in parts of the eastern United States and Western Europe where reforestation has taken place (Unger 2014; Heald and Geddes 2016). Bouwman *et al.* (2013) estimated that agricultural soil N_2O emissions increased by a factor of three during the 20th century.

Soil respiration is a major source of CO_2 to the atmosphere at a global scale (Hashimoto *et al*. 2015) that in recent decades has increased its contribution (Bond-Lamberty *et al.* 2018).

5.3 State: atmospheric composition and climate

For meteorology and climate variables, a well-developed global observation system with spatial coverage adequate to monitor regional patterns is coordinated by WMO. For atmospheric composition, however, the amount of information available varies significantly by pollutant and region. Countries in North America, Europe and East Asia, have well-developed in-situ ground-based monitoring networks for ground-level O_3 and PM, as well as SO_2, CO and, in some areas, NO and NO_2. For other pollutants, observations tend to be relatively sparse. There is a need for a global catalogue of monitoring station metadata, currently being pursued through expansion of the WMO Global Atmosphere Watch Station Information System (GAWSiS, https://gawsis.meteoswiss.ch) and Observing Systems Capability Analysis and Review (OSCAR, https://oscar.wmo.int) tool. For many regions of the world, however, ground-based networks do not have sufficient density and coverage to characterize spatially representative trends. Observations from satellites, aircraft and other platforms, as well as atmospheric chemistry and transport models, are needed to complement traditional networks.

Existing polar-orbiting satellite instruments provide global observations of a number of important air pollutants (including PM, O_3, CO, SO_2, NO_2, NH_3, formaldehyde and CH_4) albeit with relatively coarse temporal, spatial and vertical resolution (Duncan *et al.* 2014; Duncan *et al.* 2016). In some parts of the world, however, monthly average total column observations from satellites provide the only information available. Current efforts to improve understanding of the relationship between space-based and ground-based observations should help to fill data gaps in areas with sparse monitoring (e.g. Snider *et al.* 2015).

Space agencies in the Republic of Korea, the United States of America and Europe are working to deploy a constellation of geostationary satellites over East Asia, North America, Europe, North Africa and the Mediterranean to measure O_3, PM and their precursors. In geostationary orbit, these instruments will have much finer temporal and spatial resolution than current polar-orbiting satellites, providing a wealth of information about air pollution over these regions in near real-time (Committee on Earth Observing Satellites 2011).

At the other end of the spectrum of cost and complexity, inexpensive electronic sensors for measuring different pollutants are being developed, marketed to governments, businesses and even individuals, and deployed in a variety of mobile and stationary settings (e.g. Apte *et al.* 2017). The quality of information varies significantly and is currently low, but efforts are in place to better understand the performance of different sensors, and to develop standardized tests and guidance on how to deploy and use the observations gathered (UNEP 2016; Lewis *et al.* 2017; US EPA 2018b).

Increasingly, air quality information from ground-based networks as well as air quality forecasts are being made available publicly. The United States of America pioneered such systems with AirNow.gov starting in 1998, and similar information is now available in countries and cities worldwide, as well as through open source platforms (e.g. OpenAQ.org) (see Section 12.2.4).

5.3.1 Air pollution: urban to global scales

From a global public health perspective, the two most important air pollutants are PM and its components and ground-level O_3. Ambient PM may be emitted directly as a fine particle (e.g. BC, OC and soil dust) or formed in the atmosphere from emissions of gaseous precursors (e.g. SO_2, NO_X, NH_3 and NMVOC). Ground-level O_3 is not directly emitted but is formed in the atmosphere from reactions of NO_X, NMVOC, CH_4 and CO (Seinfeld and Pandis 2016). Globally, the highest annual average concentrations of $PM_{2.5}$ are seen in areas affected by windblown sand and dust (e.g. northern Africa and west Asia), fires (e.g. Central Africa and Latin America) and anthropogenic pollution (e.g. South and East Asia) (Cohen *et al.* 2017; Shaddick *et al.* 2018) (see **Figure 5.7**). From 1998 to 2012, satellite observations suggest that $PM_{2.5}$ decreased significantly over eastern North America, and increased over west Asia, South Asia and East Asia (Boys *et al.* 2014). Ground-based measurements suggest that the trends over North America, South Asia and East Asia are associated with changes in anthropogenic pollution, but the changes over west Asia are due to changes in windblown sand and dust (Boys *et al.* 2014).

Ground-level O_3 is highest in the northern mid latitudes and tropics, and peaks in the warm season. North America, the Mediterranean, South Asia and East Asia are hotspots for O_3 pollution (see **Figure 5.8**). However, high population weighted O_3 concentrations are also estimated in Central Africa, west Asia and South-East Asia (Health Effects Institute 2017).

Satellite observations have identified rapid changes in the ground-level concentrations of SO_2 and NO_2 over the last 10-15 years, with declining trends in Europe and North America, and increasing trends in some regions in East Asia, South Asia, Africa and South America (Schneider, Lahoz and van der A 2015; Geddes *et al.* 2016; Krotkov *et al.* 2016).

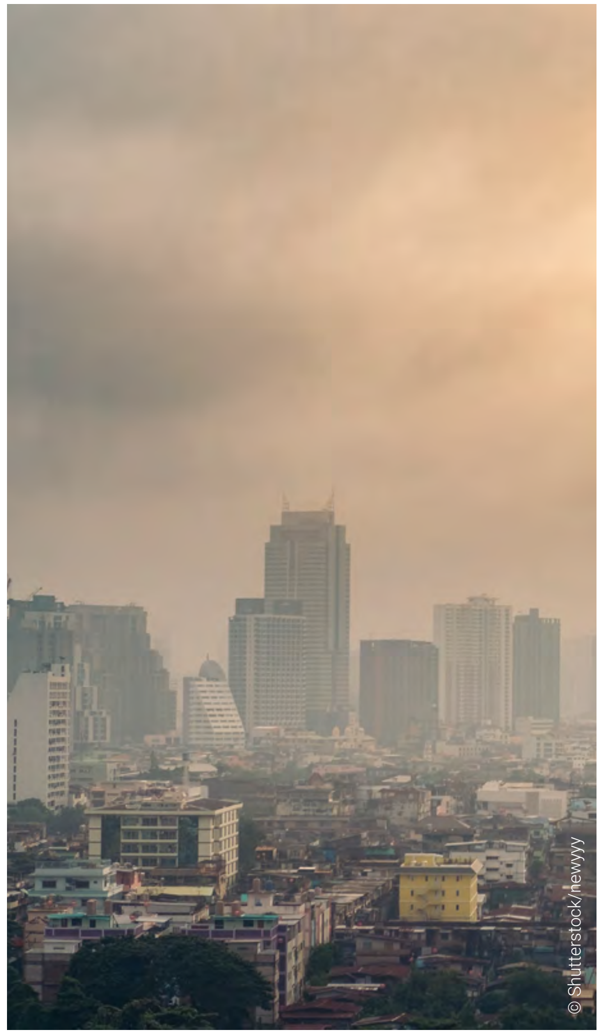
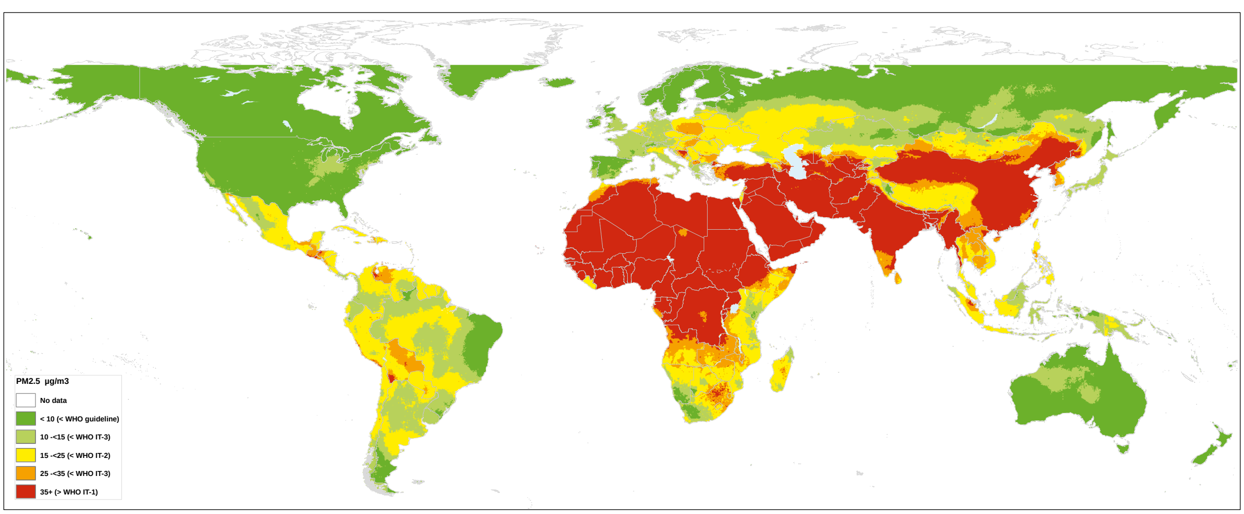


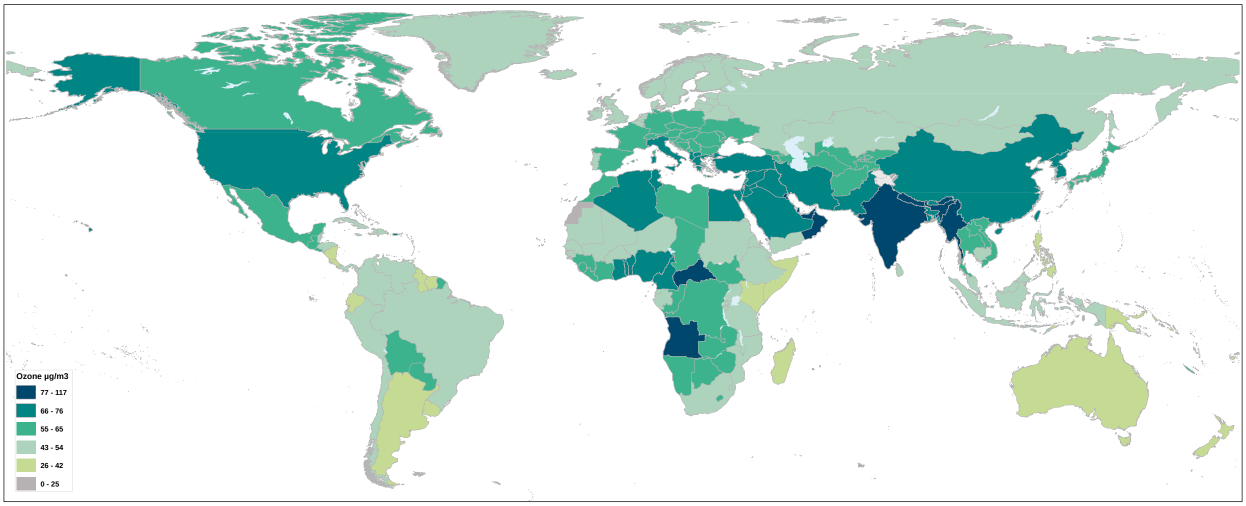
Figure 5.7: Annual average $PM_{2.5}$ concentrations in 2016 compared with the WHO Air Quality guideline and interim targets



This map combines data from satellite observations, surface monitors and an atmospheric chemistry and transport model. IT = Interim Target.

Source: Shaddick *et al.* (2018).

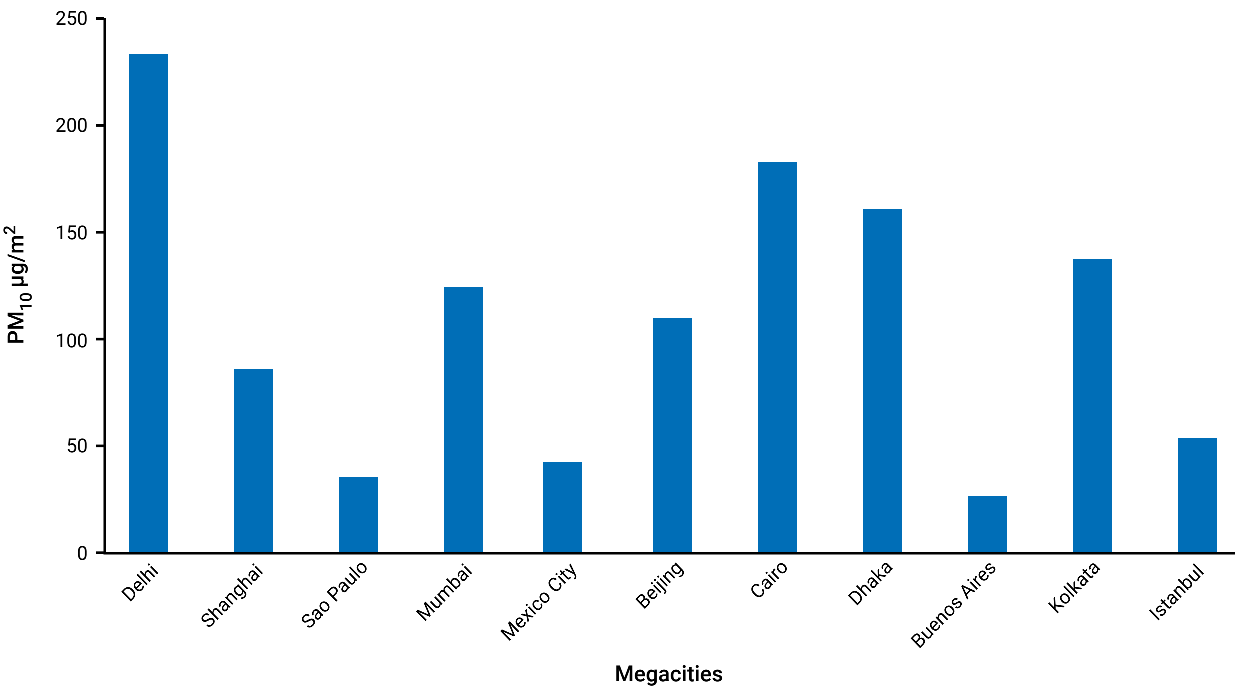
Figure 5.8: Seasonal average population-weighted O_3 concentration in 2016 for season with maximum ozone levels by country



Source: HEI (2018).

Urban areas, which are home to over half of the world's population, have higher overall levels of air pollution. A review of published $PM_{2.5}$ observations for 71 megacities (over 5 million people) for 2013 found that, of the 45 megacities with available observations, only 4 attained the WHO guideline for annual average concentrations (Cheng *et al*. 2016) **(Figure 5.9)**. Cities with the highest levels were clustered in east-central China and the Indo-Gangetic Plain. Many cities in low- and middle-income countries lack available measurements, but where data is available, 98 per cent of cities exceed the WHO guidelines for $PM_{2.5}$ or PM_{10}, compared with the 56 per cent of cities in high-income countries with available data (WHO 2016b).

Figure 5.9: Annual average PM_{10} levels for megacities of more than 14 million inhabitants with available data for the period 2011-2015



Source: WHO (2016b).

5

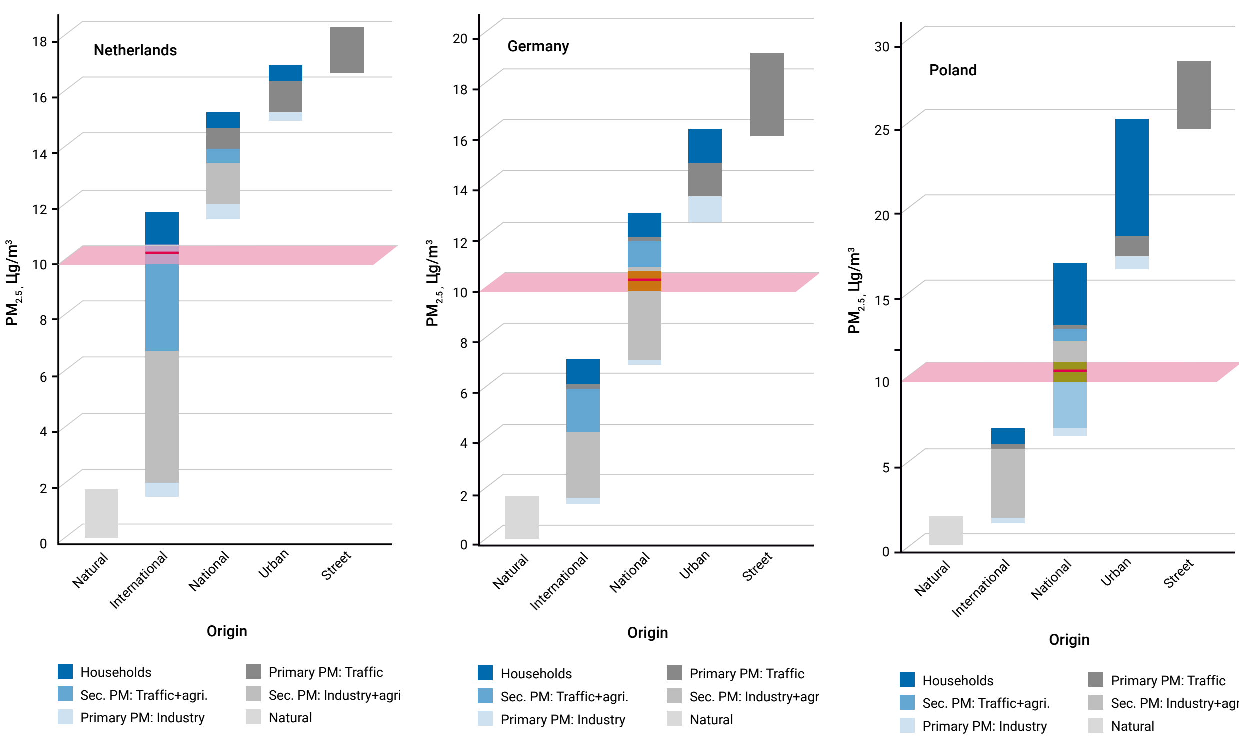
Traffic, residential fuel burning, electricity generation, industry and agriculture all contribute to urban air pollution, although the contribution of different sectors in individual cities can vary significantly (Karagulian *et al.* 2015). In growing cities across Africa, Asia and other developing regions, there has been an unprecedented rapid increase in the number of vehicles, driven by population growth and economic development (e.g. Adiang *et al.* 2017). It is projected that by 2030 there will be 41 megacities (population greater than 10 million), the majority in developing countries (United Nations 2016b). Impacts of the pollution from megacities extends far beyond the urban area with effects at local, regional and global scales (Ang'u, Nzioka and Mutai 2016; WHO 2016b).

Air pollution observed in any given location may be comprised of contributions from local, regional and even global sources **(Figure 5.10)**.

Better global models, additional monitoring and field studies, and accumulated observations from satellite-based instruments have improved our understanding of the processes and trends that drive such long-range transport of pollution. However, quantifying the absolute contributions of distant sources to observed values on a given day remains challenging. Data assembled for the Tropospheric O_3 Assessment Report (TOAR) demonstrates that recent trends in peak values upon which most health-based standards are founded are strongly decreasing in North America and Europe, and strongly increasing in parts of East Asia. However, for summer daytime average O_3 concentrations, the trends are more mixed in North America and Western Europe, with some sites showing significant increases (Chang *et al.* 2017; Schultz *et al.* 2017). This finding is consistent with observations of increasing 'background' O_3 above the boundary layer throughout the Northern Hemisphere (Task Force on Hemispheric Transport of Air Pollution 2010; Parrish *et al.* 2014). The observed increasing trend in global tropospheric O_3 from 1980 to 2010 may be due primarily to an equatorward shift in the distribution of global precursor emissions, the effect of which is larger than the increase in global methane and the total mass of other precursor emissions combined (Zhang *et al.* 2016).

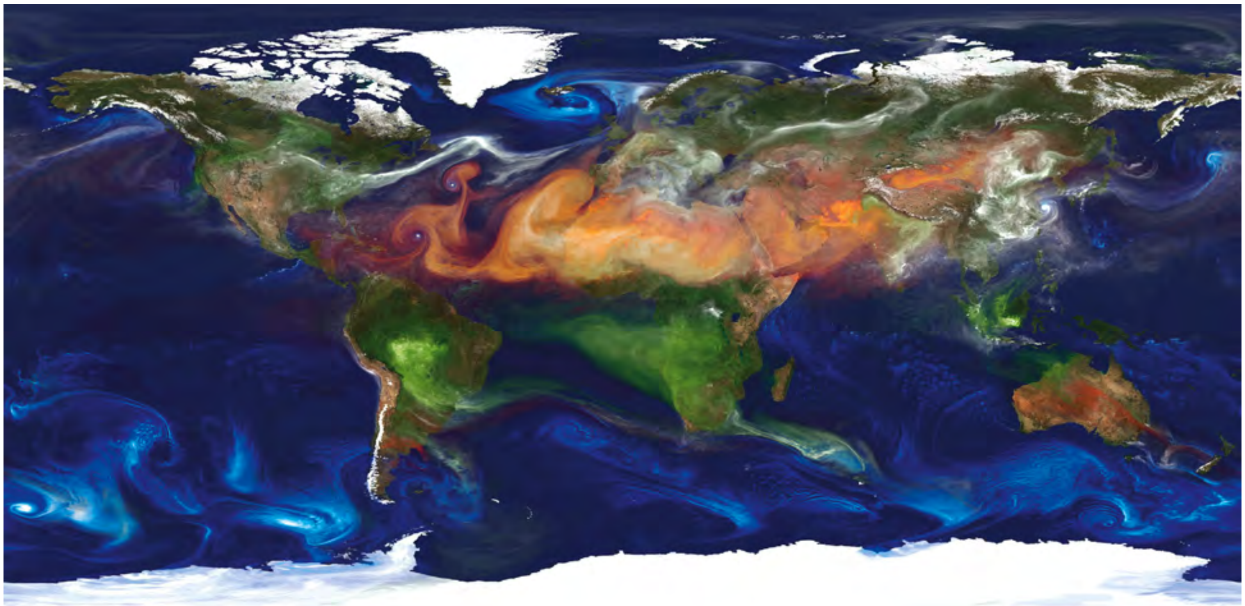
The largest source of particulate matter in the atmosphere globally, on an annual basis, is windblown sand and dust. A 'dust belt' extends from the west coast of North Africa, over the Mediterranean Basin, the Middle East, Central and South Asia, to Mongolia and China (see **Figure 5.11**). This encompasses both natural areas, such as the Sahara and Taklamakan deserts, as well as agricultural areas. Outside the dust belt, sand and dust storms (SDS) are less prevalent; however, SDS can have important local impacts in central Australia, Southern Africa (Botswana and Namibia), the Atacama in South America, and the North America Great Basin (UNEP, WMO and UNCCD 2016). People influence dust sources through land clearing and land management practices and other influences on

Figure 5.10: Model estimates of the sources of $PM_{2.5}$ observed in several cities in each of three countries shows local $PM_{2.5}$ concentrations are strongly influenced by secondary particles from transboundary sources. The source of emissions is divided into natural, international (emitted outside the country), national (emitted within the country but outside the urban area), urban (emitted within the city) and street (emitted within the immediate vicinity of the observation) and interim targets



Source: Reprinted from UNEP/UNECE (2016), based on (Kiesewetter and Amann 2014).

Figure 5.11: The Dust Belt



Using a global model, the aerosol optical depths attributable to different types of particulate matter are shown in different colours: dust (red and yellow), black and organic carbon (green), sulphate (white); and sea salt (blue). An animated version of this image is available at https://gmao.gsfc.nasa.gov/research/aerosol/modeling/nr1_movie/

Source: Puttman and da Silva (2013).

desertification (see Section 8.4.2). UNEP, WMO and UNCCD (2016) concluded that there has been little change in the frequency and severity of SDS in North Africa, the Middle East and South America over the last 30 years, but significant increases have been observed in North America, Central Asia and Australia. Klingmuller *et al.* (2016) found an increasing trend in dust over large parts of the Middle East during the period 2001 to 2012 that is correlated with climatic changes.

Transported dust contributes to a wide range of impacts: it affects climate and precipitation patterns; fertilizes distant forests and oceans; contributes to human respiratory ailments; and spreads human, animal and plant pathogens far downwind of the source region. Within the source region, dust storms may damage infrastructure, interrupt transportation and communication systems, and cause air and road traffic accidents. To better understand, forecast and mitigate these impacts, WMO has established a global Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) (UNEP, WMO and UNCCD 2016; WMO 2017b).

Fires, primarily associated with land clearing or lightning, are another large contributor to transboundary pollution. In South-East Asia, perennial forest and peatland fires associated, primarily with slash-and-burn agriculture, intensify during dry seasons (Page and Hooijer 2016; Wijedasa *et al.* 2017). In 2015, fires blanketed the region with smoke, leading to an estimated 100,000 premature deaths associated with air pollution exposure, mostly in Indonesia (Koplitz *et al.* 2016) (see Section 12.2.5). Boreal forest fires in Siberia, Canada and Alaska contribute to the deposition of BC and other particles in the Arctic, darkening the surface of snow and ice and accelerating melting (Arctic Monitoring and Assessment Programme [AMAP] 2011; AMAP 2015).

5.3.2 Persistent bioaccumulative toxic substances

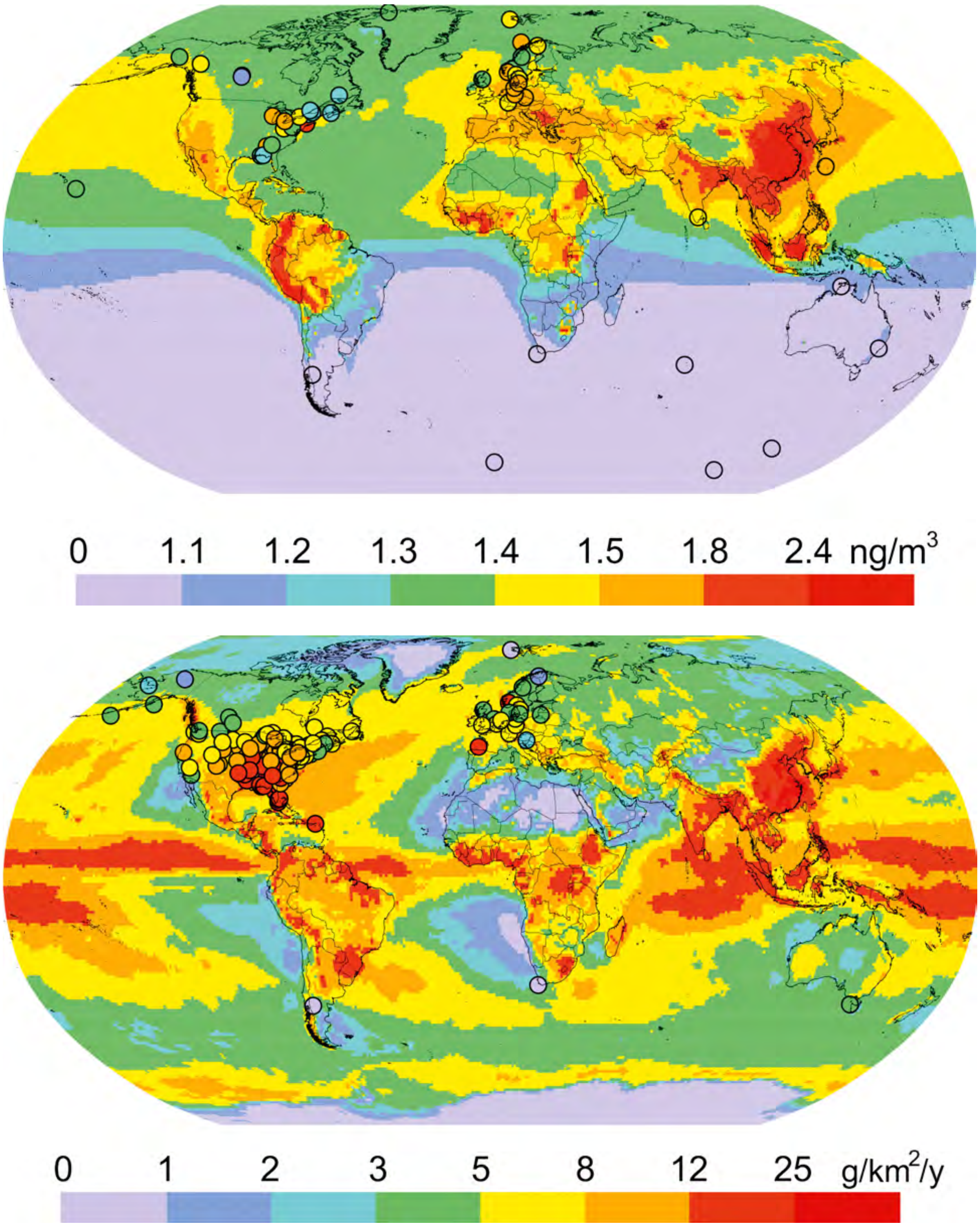
Gaseous elemental Hg is a global pollutant with the highest concentrations in East, South and South-East Asia, and in the artisanal gold mining regions of Equatorial Africa and South America (see **Figure 5.12**) (UNEP and AMAP 2018).

Concentrations of POPs that are regulated and monitored under the Stockholm Convention have been reduced in Europe, North America, and Asia and the Pacific (UNEP 2014a; UNEP 2014b; UNEP 2015a; UNEP 2015b).

Measurements of regulated POPs in Arctic air and biota show predominantly downward trends for substances that have been banned for more than 20-30 years in developed countries, but the rate of their decrease has slowed (Hung *et al.* 2016). Trends of POPs in the Arctic appear to be sensitive to changes in climate, due to increased volatilization from sources (AMAP 2014, Ma *et al.* 2011) and to changes in Arctic land-use and emission patterns, such as increases in mining and shipping (UNEP and AMAP 2011) (see also Sections 4.3.2 and 4.3.3). Although Antarctica is the Earth's continent least subject to direct human impact, low but sometimes significant contamination levels can be found there (Vecchiato *et al.* 2015). Concentrations of PAHs and PCBs in Antarctic snow have decreased over recent decades (Vecchiato *et al.* 2015).

Trends for many new PBTs, however, are not yet established, although baseline data have become available in some regions, such as Europe (UNEP 2015a). As some POPs have been regulated or banned, other unregulated PBTs have emerged as substitutes and are widely used in consumer and household items (e.g. furniture and electronics) and construction materials (Lee *et al.* 2016; Rauert *et al.* 2016). The growing

Figure 5.12: Global distribution of annual mean gaseous elemental mercury concentration in near-surface air (top) and wet-deposition flux (bottom) in 2015 simulated by a model ensemble



Circles show values observed in ground-based monitoring

Source: UNEP and AMAP (2018).

number of listed POPs and candidate substances presents a resource pressure for existing monitoring programmes (UNEP 2015a). The emission, transport and environmental fate of new unregulated PBTs differs from regulated POPs, further challenging their assessment.

5.3.3 Stratospheric O_3 and ultra-violet radiation

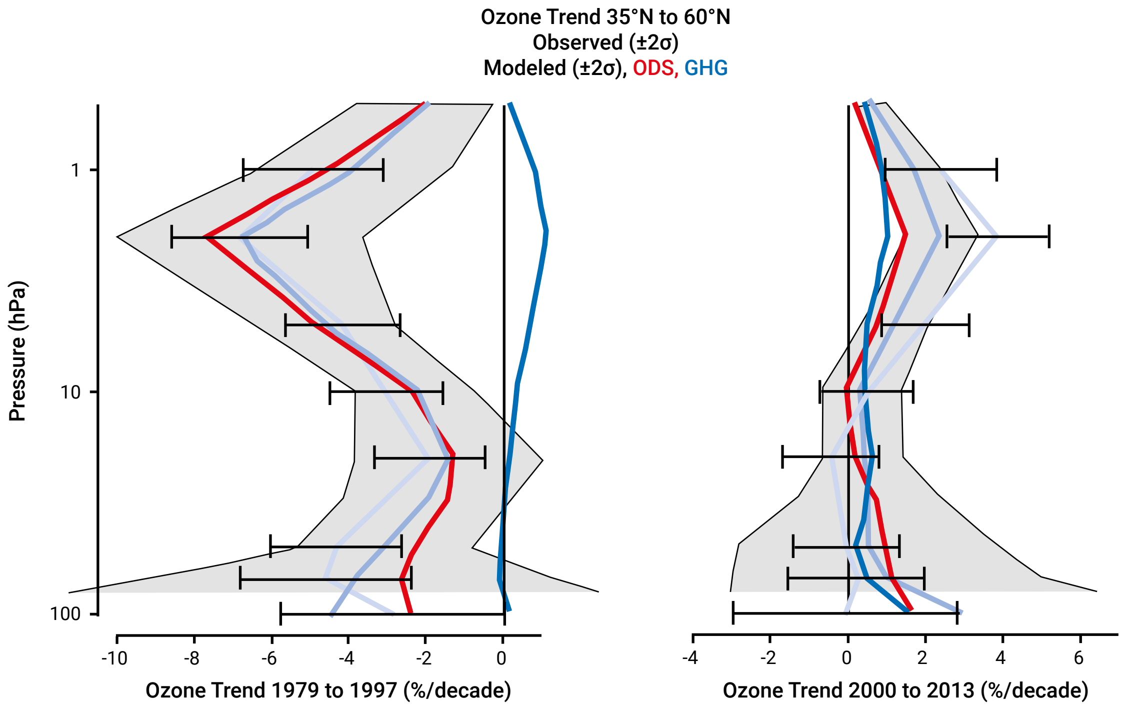
Perennial ground-based *in situ* observations of ODS show a clear decline since the implementation of the Montreal Protocol (Newman *et al.* 2007; Engel *et al.* 2018). However, the decreasing trend slowed down by about 50 per cent after 2012 for trichlorofluoromethane (CFC-11) (Montzka *et al.* 2018). There are indicators that the stratospheric O_3 layer is starting to recover. Total atmospheric column O_3 declined over most of the globe during the 1980s and early 1990s, but has remained stable since 2000, and there are indications of an increase in global-mean total column O_3 over 2000-2013 **(Figure 5.13)** (WMO 2014). Since around 2000, measured concentrations of O_3 in the upper stratosphere show an increasing trend, and modelling results indicate that decreasing ODSs and increasing GHGs, which increases stratospheric ozone by cooling the stratosphere, contributed equally to the increase in upper stratospheric ozone (WMO 2014; Harris *et al.* 2015; Chipperfield *et al.* 2017). Over Antarctica, positive trends for 2001-2013 were found for O_3 concentrations in the lower stratosphere (about 10-20 km) for austral summer and for total column O_3 for spring and summer (Kuttippurath and Nair 2017; Solomon *et al.* 2017). For the mid-latitudes (60°S and 60°N), there is no clear indication of O_3 recovery for reasons that are not clear (Ball *et al.* 2018). As ODS concentrations continue to decline throughout the 21st century, stratospheric O_3 concentrations are expected to rise, though the trends will be increasingly dominated by effects from rising GHG concentrations; thus, the time frame for stratospheric O_3 to recover to 1960 levels is uncertain (Chipperfield *et al.* 2017).

Changes in ultraviolet (UV) radiation at the Earth's surface in response to the recovery of stratospheric O_3 have not yet been documented, because such changes are still masked by varying attenuation of UV radiation by O_3, clouds, aerosols and other factors (Bais *et al.* 2018).

5.3.4 Climate change

In 2016, global averaged concentrations of CO_2, CH_4 and N_2O reached 403.3±0.1 ppm, 1853±2 ppb and 328.9±0.1 ppb, respectively, corresponding to 145 per cent, 257 per cent and 122 per cent above pre-industrial levels (WMO 2017c). The global CO_2 growth rate from 2015 to 2016 was the largest of the last 30 years (partly driven by El Niño) and the CO_2 concentration was the highest in at least the last 800,000 years. CH_4 concentrations plateaued during 1999-2006 but have been increasing since then. Studies point to a variety of different processes driving the change in CH_4, mainly changes in anthropogenic sources, permafrost melting or wetland emissions (Dean *et al.* 2018). N_2O concentrations have been increasing steadily since the mid-1980s. Concentrations of CFC

Figure 5.13: Vertical profiles of annual mean O_3 trends over 35°-60°N averaged over all available observations (black) for the periods of stratospheric ODS decline (left) and ODS increase (right), with the corresponding modelled trends for ODS changes only (red), GHG changes only (blue) and both together (grey)



Note: The ±2 standard error uncertainty range for the trends is shown by the horizontal bars for the observations and by the grey shading for the all-changes modelled trend.

Source: WMO (2014).

replacements, HCFCs and HFCs, which are potent GHGs, have been increasing exponentially since 2005, though these remain low overall and currently contribute to less than 4 per cent combined of the radiative forcing due to all GHGs. According to the National Oceanic and Atmospheric Administration Annual Greenhouse Gas Index (AGGI), radiative forcing by long-lived GHGs increased by 78 per cent between 1979 and 2016, with CO_2 accounting for about 72 per cent of this increase.

Since 1901 almost the whole globe has experienced surface warming, and it is extremely likely that anthropogenic activities caused more than half the observed increase in global mean surface temperature since the mid-20th century (Bindoff *et al.* 2013). The global mean surface temperature increase over the 1901-2012 period (see **Figure 4.2**) was approximately 0.89°C, but some regions experienced warming of greater than 2°C (Hartmann *et al.* 2013).

Trends in precipitation are less clear and differ by locations. In general, dry areas are becoming drier, and wet areas are becoming wetter, but multiple exceptions exist (Trenberth 2011; IPCC 2014; Feng and Zhang 2015). For tropical land areas, observations show a decreasing trend from the mid-1970s to mid-1990s and an increasing trend the following decade, resulting in no significant overall trend from 1951 to 2008 (Hartmann *et al.* 2013). A statistically significant increase in precipitation occurred from 1901 to 2008 for the northern mid-latitudes (30°N to 60°N) land areas; in contrast, there is only limited evidence of a long-term increase in the southern mid-latitudes (Hartmann *et al.* 2013). Observed changes in the latitudinal distribution of precipitation over land are suggestive of human influence; however, the results are still inconclusive, due to incomplete data and model uncertainties (Bindoff *et al.* 2013).

Climate change can also impact atmospheric circulations and features at global and regional levels. Observations indicate a widening of the tropical belt, a poleward shift of storm tracks and jet streams, and a contraction of the northern polar vortex since the 1970s are likely (Hartmann *et al.* 2013). Stratospheric O_3 depletion and GHG warming may have contributed to the poleward shift of the southern Hadley cell and positive trend in the Southern Annular Mode, which characterizes the north-south movement of the belt of westerly winds that circles Antarctica, during the austral summer (Bindoff *et al.* 2013). Attribution of anthropogenic influence on the poleward shift of the Hadley cell in the Northern Hemisphere is less certain (Bindoff *et al.* 2013). While many studies have indicated changes in the El Niño-Southern Oscillation (ENSO) and monsoon circulations, there are large observational and modelling uncertainties such that there is low confidence that changes, if observed, can be attributed to anthropogenic activities (Bindoff *et al.* 2013).

There is increasing evidence that climate change has led to changes in the frequency and intensity of extreme events since the mid-20th century (Trenberth 2011; Hartmann *et al.* 2013; Alexander 2016). It is likely that the frequency of extreme warm days has increased in North America, Central America, Europe, Southern Africa, Asia and Australia, and the frequency of heat waves has increased in Europe, Australia and across large parts of Asia (Hartmann *et al.* 2013). Observations have shown a general increase in heavy precipitation at the global scale (Trenberth 2011; Hartmann *et al.* 2013). Regionally, it is likely that the frequency or intensity of heavy precipitation events has increased in North America, Central America and Europe, and it is virtually certain that there has been an increase in the frequency and intensity of the strongest tropical cyclones in the North Atlantic basin since the 1970s (Hartmann *et al.* 2013). For drought, the frequency and intensity likely have increased in the Mediterranean and West Africa, and likely have decreased in central North America and north-west Australia (Hartmann *et al.* 2013).

Air pollution, stratospheric O_3 depletion, persistent pollutants and climate change are interlinked problems (see **Figure 5.1**). Climate warming agents such as BC, tropospheric O_3, CH_4 and HFCs have a relatively short lifetime in the atmosphere compared with long-lived GHGs and are referred to as short-lived climate pollutants (SLCPs) (Haines *et al.* 2017). Tropospheric O_3 contributes to warming directly as a GHG. However, O_3 also contributes to warming by impairing vegetation growth and decreasing plant uptake of CO_2 (Ainsworth *et al.* 2012). BC has a warming effect both in the atmosphere and when deposited on snow and ice. Decreasing emissions of SLCPs can decrease warming in the near term, which may be essential for achieving near-term climate targets or avoiding climate tipping points (Shindell *et al.* 2017). However, decreasing emissions of SLCPs in the near term needs to be combined with mitigation of long-lived GHGs, which dominate climate forcing over the long term (UNEP 2017c).

Other PM constituents (e.g. sulphates and nitrates) also affect climate and may cool the climate by scattering solar radiation. PM also affects climate indirectly by affecting cloud formation, leading to changes in cloud reflectivity, cloud distribution and precipitation patterns. There is still a significant amount of uncertainty on the net radiative effects of aerosols (Fuzzi *et al.* 2015).

Through its impact on synoptic and local-scale meteorology, climate change impacts air pollution and PBT concentrations in multiple, non-linear ways (UNEP and AMAP 2011; Fiore, Naik and Leibensperger 2015). Higher temperatures can increase the chemical reaction rates involving O_3 formation or reduce PM concentrations as components volatilize (Megaritis *et al.* 2013; Czernecki *et al.* 2016). Higher temperatures also increase primary emissions of POPs that can volatilize and secondary emissions by revolatilizing previously deposited POPs (Ma *et al.* 2011). Because particle-bound POPs are more efficiently removed from the atmosphere via deposition, semi-volatile POPs may last longer in the atmosphere at higher temperatures and be transported further from source regions. Higher temperatures may also increase degradation of POPs (Ma *et al.* 2011). Reduced cloud cover promotes the formation of O_3 by increasing photolysis rates (Na, Moon and Kim 2005). Higher temperatures and light intensity can also increase emissions of biogenic NMVOC (Guenther *et al.* 2012), which are O_3 and PM precursors. At the same time, higher temperatures and water stress lower stomatal uptake of O_3 and thus reduce O_3 deposition (Solberg *et al.* 2008; Huang *et al.* 2016). More rain reduces pollution by washing out PM and other pollutants. Extreme events such as heat waves and drought increase risks of high PM pollution associated with wildfires (Bowman *et al.* 2017) and dust (Achakulwisut, Mickley and Anenberg 2018). Extreme events such as floods and storms can also impact the remobilization and bioavailability of POPs (Ma *et al.* 2011).

Meteorological parameters that affect air quality often co-vary with and depend on synoptic-scale or other larger-scale phenomena. For example, surface O_3 and PM concentrations are strongly influenced by ventilation and dilution, which are governed by winds and boundary-layer height and are often correlated with temperature and humidity. A decline in the number of summertime mid-latitude cyclones travelling across North America since 1980 has been associated with increases in stagnation and O_3 pollution episodes in the eastern United States of America, offsetting some of the air quality improvement in the north-eastern United States of America from reductions in anthropogenic emissions (Leibensperger, Mickley and Jacob 2008). Extreme wintertime stagnation and pollution episodes in eastern China have been associated with melting sea ice in the Arctic during the preceding autumn and increased snowfall across Siberia during early winter (Zou *et al.* 2017).

5.4 Impacts

Activities that generate emissions threaten human health and well-being, food security and ecosystems. This section focuses on the direct impacts of changing atmospheric composition.

5.4.1 Human health

Exposure to air pollution outdoors and indoors, temperature extremes, airborne pathogens and allergens, and ultraviolet radiation directly affect human health. The following focuses on air pollution effects due to anthropogenic emissions.

Air Pollution

Exposure to indoor and outdoor air pollution was responsible for 6 million (Global Burden of Disease [GBD] Risk Factor Collaborators 2017) to 7 million (WHO 2018) premature deaths in 2016. The GBD Study estimated that long-term exposure to ambient PM was responsible for between 3.6 and 4.6 millions of those premature deaths and between 95 and 118 million years of healthy life lost from heart disease, stroke, lung cancer, chronic lung disease and respiratory infections (Cohen *et al.* 2017; GBD Risk Factor Collaborators 2017; HEI 2018). Consequently, exposure to ambient $PM_{2.5}$ is the highest environmental risk factor for the global burden of disease and sixth among all risk factors in terms of disability-adjusted life years lost, behind high blood pressure, smoking, low birth weight, high levels of blood sugar and high body mass index (GBD Cancer Collaboration 2017). The estimates of premature deaths underestimate the total number of individuals affected, because air pollution has potential effects on everyone who breathes the air, rather than being the sole reason for early death in a small subset of the population (Committee on the Medical Effects of Air Pollutants [COMEAP] 2010).

Even brief periods (minutes to hours) of exposure to high concentrations of pollutants can have significant health impacts (WHO 2006), and episodes of unusually high air pollution attract public concern (e.g. Vidal 2016; Safi 2017). However, the greatest damage to public health is associated with long-term exposure – living in areas of high annual average exposure (HEI 2017). Importantly, there is no known safe level of annual average $PM_{2.5}$ exposure (WHO 2013).

About 43 per cent of the world's population, primarily in low-income countries, uses biomass for heating and cooking. The resulting indoor and outdoor air pollution contributes to acute lower respiratory infections (ALRTI) and pneumonia among children, and chronic obstructive pulmonary disease (COPD) and lung cancer among adults (WHO 2007; Sumpter and Chandramohan 2013; WHO 2018). The GBD Study attributed between 66 and 88 million disability-adjusted life years (DALYs) lost, and between 2.2 and 3.0 million premature deaths in 2016 to household air pollution (GBD Risk Factor Collaborators 2017), whereas WHO estimated the burden to be approximately 3.8 million premature deaths (WHO 2018).

An additional 0.09 to 0.38 million deaths in 2016 from chronic lung disease were attributed to ambient ground-level O_3 exposure (GBD Risk Factor Collaborators 2017). Associations of mortality with other gases are well established, notably NO_2 (a marker of traffic pollution) and SO_2 (a marker of industrial pollution) (WHO 2013). Because these are markers of mixtures, it is unclear to what extent effects associated with them are caused by the gases themselves or by correlated pollutants (WHO 2013; COMEAP 2018).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The number of deaths attributable to air pollution varies widely among countries, reflecting different pollution levels as well as differences in population size, demographics, underlying rates of disease and other socioeconomic characteristics **(Figure 5.14)**

Between 2010 and 2016, deaths attributable to ambient $PM_{2.5}$ exposure increased by 11% per cent globally, due to increased air pollution, as well as growth and ageing of the population. In 2016, 95 per cent of the world's population lived in areas with levels of $PM_{2.5}$ exceeding the WHO air quality guideline (HEI 2018). While mortality attributable to $PM_{2.5}$ has declined in Western Europe and North America, many other regions have seen sharp increases. Deaths attributable to ground-level O_3, though much fewer, have increased nearly 60 per cent globally between 1990 and 2015, with increases in some countries as high as 250-400 per cent (HEI 2017).

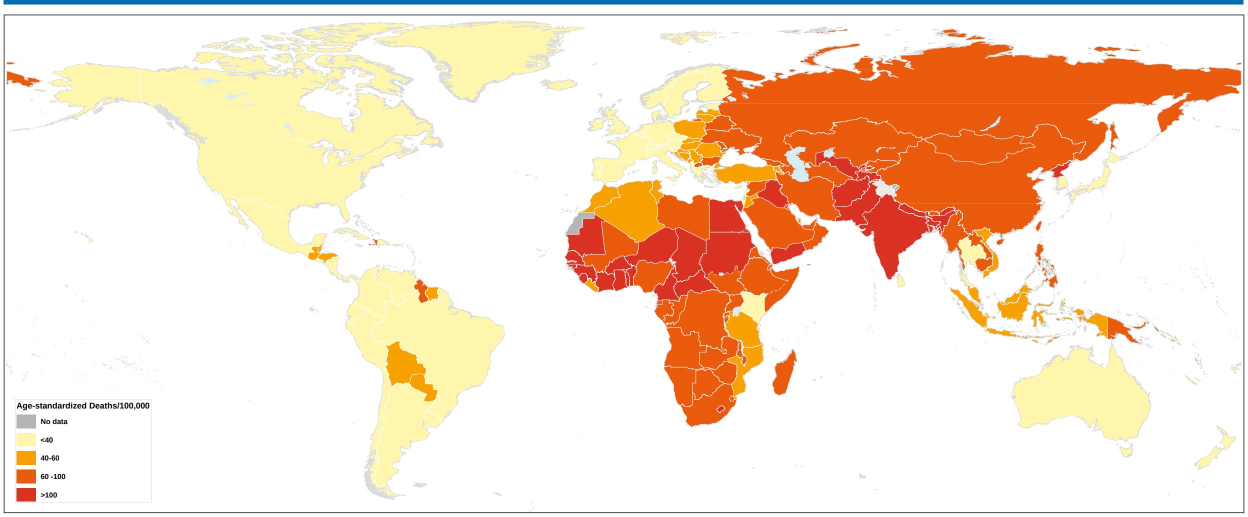
In addition to premature mortality, air pollution contributes to a wide range of chronic and acute diseases, especially cardiovascular (Brook *et al.* 2010; McCracken *et al.* 2012) and respiratory disease (American Thoracic Society 2000). Studies suggest associations between air pollution and other diseases such as diabetes (Eze *et al.* 2015); adverse birth outcomes (Stieb *et al.* 2012; Li *et al.* 2017) including premature births, low birth weight (Fleischer *et al.* 2014) and birth defects (Farhi *et al.* 2014); and neurological ailments, including dementia (Calderon-Garciduenas and Villarreal-Rios 2017). Emerging research highlights the potential interactions between air pollution and airborne pathogens and allergens (Hussey *et al.* 2017; Liu *et al.* 2018).

People who are elderly, very young, with pre-existing cardio-respiratory diseases or of low socioeconomic status are most susceptible to air pollution (Sacks *et al.* 2011). Women and children have higher exposures to air pollution indoors, where cooking and heating with solid fuels is the major source (Smith *et al.* 2014). There is increasing evidence that indoor smoke contributes to cataracts, the leading cause of blindness worldwide (Clougherty 2010; Sacks *et al.* 2011; Global Alliance for Clean Cookstoves 2014; Villeneuve *et al.* 2015; WHO 2016b).

The economic impacts of life years lost, increased health care and lost worker productivity due to air pollution are considerable. Premature mortality due to ambient and household air pollution in 2013 was estimated to cost the world's economy US$ 5.1 trillion in welfare losses (World Bank and Institute for Health Metrics and Evaluation 2016). This is equivalent to the 2013 gross domestic product (GDP) of Japan. WHO (2015) estimated that air pollution in Europe in 2010 cost US$ 1.575 trillion per year. In 2011, the US EPA estimated emission controls implemented as a result of the 1990 Clean Air Act Amendments avoided US$ 1.3 trillion in damages in 2010 (US EPA 2011). The impact of $PM_{2.5}$ air pollution on the labour force in China in 2007 was estimated to create economic losses of 346 billion yuan (approximately 1.1 per cent of GDP) (Xia *et al.* 2016). A recent OECD analysis estimated the combined cost of ambient and household air pollution in Africa to be US$ 450 billion in 2013 (Roy 2016).

Asia had the highest absolute number of deaths in 2016 attributable to $PM_{2.5}$ exposure, due to its large populations and high levels of industrial activity. However, $PM_{2.5}$ exposures have begun to decline in China but are increasing in parts of South Asia (HEI 2018). Asian countries also bear the largest burden of air pollution caused by the production of goods consumed in other regions of the world, primarily Western Europe and North America. For example, 97 per cent of $PM_{2.5}$ related deaths in East Asia were associated with emissions in East Asia, but only 80 per cent were associated with goods or services consumed in East Asia. Consumption in Europe and Russia and in North America of goods made in East Asia were estimated to contribute 7 per cent and 6 per cent, respectively, to the $PM_{2.5}$ mortality burden in East Asia (Zhang *et al*. 2017) **(Figure 5.15)**.

Figure 5.14: Deaths per 100,000 people in 2016 attributable to ambient $PM_{2.5}$ air pollution; age-standardized data



Age standardization allows the estimates to be compared for countries with different age distributions. Note that these estimates do not include deaths attributable to exposure to household air pollution

Source: Adapted from HEI (2018).

Figure 5.15: Percentage of $PM_{2.5}$ related deaths in a region indicated by the column due to (a) emissions produced or (b) goods and services consumed in the region indicated by the row

		China and East Asia	India and Rest of Asia	Europe and Russia	Middle East and North America	North America	Latin America	Sub Saharan Africa and Rest of World
Where air pollution was emitted	China and East Asia	97%	3%	1%	1%	2%	1%	0%
	India and Rest of Asia	1%	93%	1%	2%	0%	0%	2%
	Europe and Russia	1%	0%	94%	18%	1%	0%	1%
	Middle East and North Africa	0%	3%	2%	78%	0%	0%	5%
	North America	0%	0%	1%	1%	95%	2%	0%
	Latin America	0%	0%	0%	0%	1%	97%	0%
	Sub Saharan Africa and Rest of World	0%	0%	0%	0%	0%	0%	93%
Where associated goods were consumed	China and East Asia	80%	4%	3%	3%	6%	4%	2%
	India and Rest of Asia	3%	84%	2%	3%	1%	1%	2%
	Europe and Russia	7%	4%	86%	24%	5%	6%	4%
	Middle East and North Africa	2%	3%	4%	64%	2%	1%	4%
	North America	6%	3%	3%	4%	82%	12%	2%
	Latin America	1%	0%	1%	1%	4%	75%	1%
	Sub Saharan Africa and rest of World	1%	1%	1%	1%	1%	1%	84%

Source: Based on Zhang *et al.* (2017).

Stratospheric ozone depletion

The health risks of stratospheric O_3 depletion occur as a result of increased levels of biologically damaging wavelengths of UV radiation reaching the Earth's surface. Although some exposure to UV is necessary, too much exposure damages the skin and eyes and can cause immune suppression. Impacts include sunburn, keratinocyte (previously called non-melanoma) cancers, cutaneous malignant melanoma (CMM), Merkel cell carcinoma, photoconjunctivitis. photokeratitis (e.g. snow blindness), cataracts, pterygium and conjunctival melanoma.

In recent decades, most countries with predominantly fair-skinned populations have experienced a steady increase in the incidence rates of CMM which is responsible for about 80 per cent of the deaths due to skin cancer (Lucas *et al.* 2015). Excessive exposure to UV radiation accounts for 60-90 per cent of the risk for CMM (Olsen, Carroll and Whiteman 2010; WHO 2004). Increasing incidence rates of CMM and other UV-related adverse health impacts are unlikely to be due to changes in UV exposure due to stratospheric O_3 depletion, but rather to increases in risky sun exposure behaviour (Lucas *et al.* 2015). However, without the Montreal Protocol, incidence of skin cancer may have been 14 per cent greater, affecting 2 million people by 2030 (van Dijk *et al.* 2013).

Climate change

Over the coming decades to centuries, adverse health effects from climate change are forecast to greatly exceed any potential health benefits (Smith *et al.* 2014; Watts *et al.* 2017). The effects of climate change on human health can be classified as direct (e.g. heat waves, storms), less direct (e.g. changes in disease-vector ecology, reductions in water supply, or exacerbation of air pollution episodes) and diffuse (Butler 2014; Melillo, Richmond and Yohe 2014). The category of diffuse effects could have the largest burden of disease through means such as conflict (Kelley *et al.* 2015), migration (Piguet, Pecoud and de Guchteneire eds. 2011) and famine. Mental health effects arise from all three categories (e.g. post-traumatic stress disorder).

The health impacts of a changing climate will be inequitably distributed globally. Climate change and increasing climate variability "worsen existing poverty, exacerbate inequalities, and trigger both new vulnerabilities and some opportunities for individuals and communities" (IPCC 2014, p. 796).

Buildings and roads retain heat more than rural landscapes and depress humidity, creating urban heat islands. In northern mid-latitudes and subtropics, nights are up to 4°C warmer and

10-15 per cent drier in urban areas compared with surrounding rural areas. In northern Africa, the number of nights with exceptional heat stress is around ten times higher in urban areas than in rural areas (Fischer, Oleson and Lawrence 2012).

5.4.2 Food security

The Food and Agriculture Organization of the United Nations (FAO 2008) describes four dimensions of food security: availability, related to quantity; access, including affordability; utilization, related to meeting nutritional needs and food safety; and stability, related to the temporal variation in the other dimensions.

Availability: Current levels of ground-level O_3 decrease yields of key staple crops – including wheat, soybean, maize and rice – by 2-15 per cent depending on crop types and locations (Feng and Kobayashi 2009; Van Dingenen *et al.* 2009; Fishman *et al.* 2010; Avnery *et al.* 2011). Global estimates of damage are uncertain because different cultivars of crops have different sensitivities and not all crops have been studied. The economic implications of loss of crop productivity are substantial. For example, elevated O_3 concentrations in the United States of America reduce maize and soybean production by about 10 per cent and 5 per cent, respectively, at a cost of US$9 billion annually (McGrath *et al.* 2015).

Climate change already affects crop production through changes in average and extreme temperatures and precipitation, the spread and impacts of invasive weeds and pests and deforestation. Although increased CO_2 fertilization (see Section 4.4.3) is thought to offset negative impacts, the interactions between changes in CO_2, O_3, nitrogen, water availability and temperature are still not well understood (Schlenker and Roberts 2009; Porter *et al.* 2014).

Yields in tropical countries are expected to suffer the most serious impacts, while some temperate regions may benefit from higher yields, expansion of productive areas and longer growing seasons (though these benefits may be offset by increasingly frequent extreme events, temperature and water stresses and ineffective adaptations) (Schmidhuber and Tubiello 2007; Gornall *et al.* 2010; Porter *et al.* 2014). In short, the impact of climate change on crop production will be felt most heavily in developing countries where large numbers of people depend on agriculture for their livelihoods, food insecurity is high and adaptive capacity low. Climate change impacts on the availability and distribution of aquatic species are also expected to disproportionately affect developing countries (see Section 7.3.2).

Higher temperatures are likely to adversely affect livestock productivity by changing the availability of pasture, fodder crops and water (Andre *et al.* 2011; Renaudeau *et al.* 2011; Porter *et al.* 2014). The impacts of climate change on livestock diseases remain difficult to predict and highly uncertain (Mills, Gage and Khan 2010; Tabachnick 2010).

Access: Climate change exerts upward pressure on global food prices (Porter *et al.* 2014), disproportionately affecting poor consumers who may spend a significant proportion of their income on food, with implications for health and nutrition (Springmann *et al.* 2016). Women and girls disproportionately suffer from both the health consequences of nutritional deficiencies and the greater burdens of caregiving for others who are ill (WHO 2014; FAO 2016).

Utilization: Higher temperatures and higher CO_2 levels are associated with lower protein content of grains (Porter *et al.* 2014; Feng *et al.* 2015) and reduced micronutrient content of grains and legumes (Myers *et al.* 2014).

The nutritional content and safety of food supply is affected by pollution, primarily by PBTs, including Hg and POPs. Hg can travel long distances in the air and water, bioaccumulate and biomagnify up food chains, reaching levels that can be dangerous to the health of ecosystems and humans (Gibb and O'Leary 2014; Sundseth *et al.* 2017). Concentrations of methylmercury in the blood of populations that consume top marine predators, such as indigenous Arctic people, are among the highest recorded globally, giving rise to serious health concerns (UNEP 2013a; UNEP 2013b). Hg is toxic to the central nervous system (CNS) leading to cognitive and motor dysfunction (Karagas *et al.* 2012; Antunes dos Santos *et al.* 2016; Sundseth *et al.* 2017). Hg exposure also increases the risk of cardiovascular diseases, causes kidney damage, adversely affects the reproductive, endocrine and immune systems, and leads to premature death (Rae and Graham 2004; AMAP 2009; Rice *et al.* 2014).

Similarly, POPs and other PBTs can travel long distances and bioaccumulate up food chains (e.g. Gibson *et al*. 2016; Ma, Hung, and Macdonald 2016). A wide range of health effects has been associated with exposure to POPs, including changes to the reproductive, endocrine, immunologic and neurologic systems, cancer, dermal and ocular changes, and reduced birth weight (Damstra 2002; El-Shahawi *et al.* 2010; Fry and Power 2017). The exposure of pregnant and breastfeeding women to POPs is of particular concern, as POPs can cross the placenta and the blood-milk barrier, which may increase the risk of adverse developmental outcomes in children (Vizcaino *et al.* 2014; Women in Europe for a Common Future and Women International for a Common Future 2016).

Little is known about the potential health effects of some chemicals that have substituted for banned POPs, such as non-polybrominated diphenyl ether (PBDE) organophosphate flame retardants. Human exposure to such flame retardants in the United States of America has been observed to be increasing over the last decade (Hoffman *et al.* 2017).

Stability: The increasing frequency and severity of extreme weather caused by climate change will have serious consequences for the stability of food prices and food supply, such as the wheat harvest failure and price spike experienced following the 2010 Russian heat wave (Otto *et al.* 2012; Porter *et al.* 2014). Droughts, floods and other weather-related disasters can lead to acute, localized food crises, particularly in countries with pre-existing vulnerabilities such as high levels of poverty and undernutrition. For example, climate change contributed to the drought that led to the 2011 East African food crisis and ultimately contributed to famine in Somalia (Bailey 2013; Lott, Christidis and Stott 2013; Coghlan *et al.* 2014). If transport infrastructure supporting exports from major crop-producing regions is disrupted by acute weather shocks, the impacts on food security could be more widespread (Bailey and Wellesley 2017).

5.4.3 Ecosystems

Air pollution, climate change, UV radiation and PBTs all have effects on the health of natural ecosystems and wildlife. These adverse impacts in turn affect the services provided to humans by those ecosystems, or 'nature's contribution to people' (NCP) (Diaz *et al.* 2018).

Since the 1970s, international attention has focused on air pollution in the form of wet and dry deposition of sulphur and nitrogen, often referred to as 'acid rain', which led to acidification of soils and fresh water, and damage to vegetation and fish kills. In Asia and Africa, significant increases and decreases in sulphur deposition have been observed depending on location (Vet *et al.* 2014). In Western Europe and eastern North America, after decades of declining sulphur emissions and deposition levels, acidification is declining or slowing, and some forests and lakes are showing signs of recovery (Maas and Grennfelt eds. 2016). As sulphur emissions have decreased due to the implementation of emission controls, recent assessments have focused attention on the effect that humans have had on the global nitrogen cycle and its implications.

Human activity, mainly through combustion and fertilizer production, are responsible for as much nitrogen fixation as natural and unmanaged ecosystems, significantly altering the nitrogen cycle from its pre-industrial state (Fowler *et al.* 2015). Since 2000, nitrogen deposition has decreased in North America and Europe and increased in Africa and Asia, directly corresponding to decreases of NO_X and increases in NH_3 continent-wide emissions (Zhao *et al.* 2017). Nitrogen deposition exceeds critical loads over large parts of Europe and the area of exceedance has shown little change in recent decades (Hettelingh *et al.* 2015). High levels of nitrogen deposition contribute to the eutrophication of aquatic ecosystems and can affect terrestrial plant communities, possibly favouring dominant species, which in turn affects insects, birds and other animals. The loss of biodiversity due to excess nitrogen deposition is very likely to be occurring in many parts of the world, although the impacts have not been well quantified. Changes in climate, land use and other global changes will continue to alter the nitrogen cycle in the future, with consequences for ecosystems and human health (Fowler *et al.* 2015).

Marine ecosystems are also affected by air pollution, climate change and PBT pollution, for instance through the distribution of oceanic dissolved nutrients and oxygen (York 2018). Human activity is now increasing the inputs of all fixed nitrogen to the oceans by about 50 per cent (more in local hotspots near high emission regions in South-East Asia, Europe and North America) and atmospheric transport is now the dominant route contributing anthropogenic nitrogen into the open ocean beyond the continental shelf (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection [GESAMP] 2018). Harmful algal blooms in turn can contribute to respiratory health impacts through airborne transmission of aerosols (Centers for Disease Control and Prevention 2017).

Ozone exposure can affect plant growth, flowering, pollination and susceptibility to pathogens, with impacts on species composition and biodiversity (Fuhrer *et al.* 2016). Critical load thresholds have been identified for some terrestrial ecosystems (International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops 2017), but there are many ecosystems for which O_3 sensitivity is poorly understood.

The full extent of PBT exposure and their biological effects on wildlife and natural ecosystems is still not well known and is an area of active research (AMAP 2017). However, given the widespread presence of PBTs in the environment, the potential exists for long-term damage to food chains and ecosystem functions especially in sensitive areas, such as the Arctic (AMAP 2011; AMAP 2016; AMAP 2017).

5.4.4 Social well-being

Beyond the impacts on human and ecosystem health and food security, changes in the atmosphere have negative impacts on social well-being, or welfare.

Air pollution degrades materials and coatings, decreasing their useful life and generating costs for cleaning, repair and replacement. When the materials affected are structures or objects of cultural significance, the damage can be priceless (Watt *et al.* eds. 2009). In Europe, visible pollution damage to cultural heritage sites and artworks was highlighted as a justification for air pollution control policies (Di Turo *et al.* 2016; Maas and Grennfelt eds. 2016). In India, the government has taken steps to protect, in addition to public health, the white marble Taj Mahal, which has become discoloured over time due to high levels of PM, possibly from the open burning of municipal solid waste (Bergin *et al.* 2015; Raj *et al.* 2016).

Sand and dust storms, fires and extreme weather events all create disruptions to society, transportation and economic activity. Such events can be a drag on a local economy and may also drive dislocations and migration (Hanlon 2016). In the short term, increased pollution levels affect worker productivity. These effects are not limited to outdoor workers or to extreme pollution levels (Chang *et al.* 2016; Zivin and Neidell 2018). In the longer term, elevated pollution exposures have been associated with poor educational and labour-market performance, creating a long-term human capital deficit (Zivin and Neidell 2018).

5.5 Response: policies and governance

A wide variety of governance approaches and policy instruments have been used to help mitigate the sources and impacts of air pollution, climate change, stratospheric O_3 depletion and PBTs, including the following.

- **Planning regimes,** strategies or action plans designed to achieve ambient air quality standards or objectives or attain emission ceilings, combined with analyses and environmental impact assessments.
- **Command and control**, including technology, emissions or ecosystem restoration standards; record-keeping and reporting requirements, or limits on manufacture, trade or use of specific chemicals or products; each of which are implemented through permitting and enforcement programmes.
- **Market interventions**, including economic instruments, such as taxes, fees or markets for tradable emission rights, as well as loans and subsidies.

- **Public information**, including product labelling, air quality forecasting, near real-time observations and training.
- **Cooperative frameworks**, including international agreements and voluntary sectoral standards or initiatives.

The effectiveness of specific examples of these policies is explored further in Chapter 12.

Different governance approaches have been adopted at local, provincial, country and international scales depending on the specific institutional, economic, technological and political contexts. Often multiple complementary approaches are deployed simultaneously to address a single issue or source. Different mixes of approaches may be used to address similar issues, even in a single jurisdiction.

The existence and extent of implementation of air-related policies also vary widely based on differences in institutional capacity and culture in different regions of the world and at different spatial scales. In some regions, such as North America and Europe, there are well-developed, federated systems of national, provincial and local policies and enforcement programmes designed to achieve common policy objectives. In other regions, international agreements or national legislation may exist, but implementation and enforcement are weak due to a lack of institutional capacity at the national or subnational scale. In some regions, city governments are developing the primary policy response to these issues, with simultaneous benefits for other parts of their countries.

Climate change, stratospheric O_3 depletion and PBTs have been recognized as shared global problems. **Table 5.2** lists some global environmental agreements that have been developed to motivate, enable and coordinate ongoing efforts to address these challenges. These set out common objectives and obligations, which are implemented through different policies developed at national to local levels. One of the most successful global agreements is the Vienna Convention and Montreal Protocol to address stratospheric O_3 depletion, which in 2009 became the first United Nations convention to be ratified by all United Nations member states. The most recent amendment to the Montreal Protocol, the 2016 Kigali Amendment, is designed to limit the impact of ODS substitutes on climate change.

Adopted in 1992, the United Nations Framework Convention on Climate Change (UNFCCC) has led to the negotiation of a series of protocols and agreements on “common but differentiated responsibilities” to address GHG emissions (United Nations 1992). The UNFCCC divides countries into developed (Annex I) and developing countries. This differentiation has been key to the design of mechanisms to transfer between countries the technology and resources needed to mitigate emissions (including Activities Implemented Jointly, Clean Development Mechanism and Joint Implementation). Under the Kyoto Protocol and Doha Amendment, Annex I countries agreed to specific emission reduction commitments. The second commitment period (2013-2020) of the 1997 Kyoto Protocol has yet to be approved by a quorum of 144 nations. The 2015 Paris Agreement set the goal of limiting the global average temperature increase to well below 2°C above pre-industrial levels by 2100, with ambition to limit the increase to less than 1.5°C. All countries are required to present periodically to the Convention Secretariat national GHG inventories and Nationally Determined Contributions (NDCs), or emission reduction commitments. To achieve the 1.5°C goal, GHG emissions need to be decreased significantly in the coming years and be brought to net zero by around mid-century (see Chapters 21 and 22). Studies have suggested that there is a greater than 90 per cent chance of exceeding

Table 5.2: Global environmental agreements relevant to climate change, stratospheric O_3 depletion and PBTs

Climate change

- 1992 United Nations Framework Convention on Climate Change (UNFCCC)
- 1997 Kyoto Protocol
  - 2012 Doha Amendment
- 2016 Paris Agreement

Stratospheric O_3 depletion

- 1985 Vienna Convention for the Protection of the Ozone Layer
- 1987 Montreal Protocol on Substances that Deplete the Ozone Layer
  - 1990 London Amendment
  - 1992 Copenhagen Amendment
  - 1997 Montreal Amendment
  - 1999 Beijing Amendment
  - 2016 Kigali Amendment

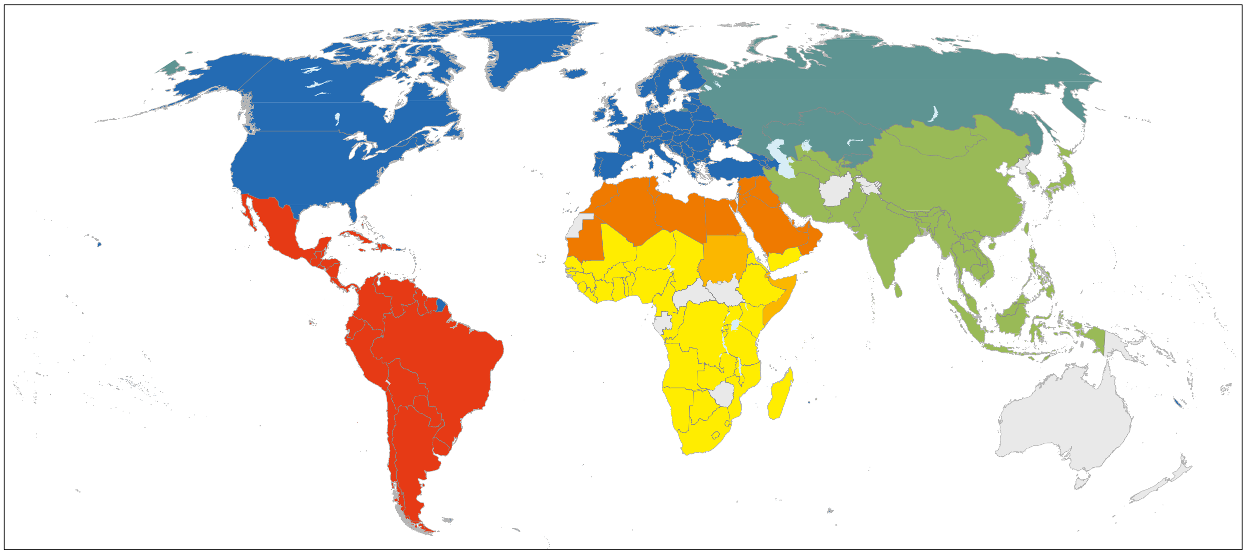
Persistent bioaccumulative toxic chemicals (e.g. POPs and Hg)

- 1989 Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal
- 1998 Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade
- 2001 Stockholm Convention on Persistent Organic Pollutants
- 2013 Minamata Convention on Mercury

2°C warming under the current pledges submitted by national governments, which achieve only a third of the mitigation required to be on a least cost path to stay below that threshold. However, pathways towards staying below 1.5°C and 2°C are still technically feasible (Xu and Ramanathan 2017).

Although air pollution travels around the world, there is no single global agreement addressing air pollution; rather there is a patchwork of regional intergovernmental agreements **(Figure 5.16)**. In general, this patchwork has good geographic coverage, but is uneven in terms of the coverage of pollutants, sources and capabilities. Furthermore, this patchwork does not encourage the transfer of experience and resources from richer to poorer countries. The oldest and most-developed among these is the 1979 Convention on Long-Range Transboundary Air Pollution (CLRTAP) organized under the United Nations Economic Commission for Europe (Sliggers and Kakebeeke eds. 2004; Maas and Grennfelt eds. 2016). In the Russian Federation and Central Asia, the CLRTAP overlaps with the grouping of agreements under the umbrella of the Asia and the Pacific Clean Air Partnership. There are three regional agreements on air pollution in Africa which overlap each other and have a few members in common with the Council of Arab Ministers Responsible for the Environment.

Figure 5.16: Map of groupings of selected regional multilateral air pollution agreements



1979 United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (Geneva)
1998 Acid Deposition Monitoring Network in East Asia (EANET)
1998 Malé Declaration on Control and Prevention of Air Pollution and its likely Transboundary Effects for South Asia
2002 Association of Southeast Asian Nations (ASEAN) Agreement on Transboundary Haze Pollution
2006 Framework Convention on Environmental Protection for Sustainable Development in Central Asia (Ashkhabad)
2015 Asia and the Pacific Clean Air Partnership
2008 Eastern Africa Regional Framework Agreement on Air Pollution (Nairobi)
2008 Southern African Development Community Regional Policy Framework on Air Pollution (Lusaka)
2009 West and Central Africa Regional Framework Agreement on Air Pollution (Abidjan)
1986 Council of Arab Ministers Responsible for the Environment (CAMRE)
2008 Intergovernmental Network on Air Pollution for Latin America and the Caribbean
No agreements

To guide their air pollution policies, many countries have developed national ambient air quality standards, or guidelines for a number of common pollutants (Kutlar Joss *et al.* 2017). These can differ with respect to the pollutant targeted, concentration level, averaging time, frequency of occurrence and measurement protocols, making comparisons of stringency difficult. In 2005, a WHO expert panel developed a set of air quality guidelines that are intended to be globally applicable for general population exposure and a set of recommended interim targets for some pollutants for areas that exceed the guidelines (WHO 2006; see **Table 5.3**). The interim targets were suggested for use by highly polluted areas as incremental steps towards achieving the guideline values. Each interim target is associated with a specified decrease in mortality risk (WHO 2006).

The ability of governments and the public to compare air quality monitoring data to such guidelines and standards and associated information about health benefits has been important in developing awareness and motivating mitigation. Thus, improving air quality monitoring infrastructure and the use of air quality and health effects information in benefit-cost analyses of mitigation measures were identified as priorities in the GEO-6 regional assessments.

Significant successes have been achieved through national and international policy and regulatory structures that have been developed over recent decades, as evidenced by the declining trends in emissions and increasing trends in activity and production (see Section 5.2). However, past policy responses may not be well suited to addressing the problems and sources

Table 5.3: WHO Air Quality Guidelines and Interim Targets

Pollutant	Averaging time	Unit	Interim targets			Air quality
			1	2	3	Guideline
PM_{10}	Annual	μg/m³	70	50	30	20
	24 hours	μg/m³	150	100	75	50
$PM_{2.5}$	Annual	μg/m³	35	25	15	10
	24 hours	μg/m³	75	50	37.5	25
NO_2	Annual	μg/m³	–	–	–	40
	1 hour	μg/m³	–	–	–	200
SO_2	24 hours	μg/m³	125	50	–	20
O_3	8 hours	μg/m³	160	–	–	100
CO	1 hour	mg/m³	–	–	–	30

Source: WHO (2006).

Box 5.1: UNEA 3/8 Resolution

Preventing and Reducing Air Pollution to Improve Air Quality Globally

The resolution urges Member States to:

- Take action to decrease all forms of air pollution
- Establish systems to monitor air quality and emissions
- Set ambitious air quality standards
- Address short lived climate pollutants as part of national action plans
- Integrate air pollution management into national development planning
- Create awareness of air pollution costs and benefits of air pollution control
- Strengthen national and sub-national capacity for air quality management

In addition, it calls for strengthened cooperation to address air pollution at the local, national, regional and global levels. The resolution also requests UN Environment to undertake additional technical support, capacity building and analysis to support Member States in improving air quality.

that remain or that are emerging, particularly in the near term. Particularly if government capacity or regulatory structures are lacking, responses that engage a broad mix of stakeholders to integrate air-related concerns into broader policy and investment decisions (e.g. transportation planning, land-use planning, economic development investments, behavioural change) may be more capable of addressing diffuse sources of emissions and promoting innovation.

Cities have been important centres of policy innovation and policy integration and continue to provide important opportunities for progress. The non-governmental organization Clean Air Asia is a leading example of efforts in this arena, bringing together city governments, national ministries, industry and other stakeholder groups from more than 1,000 cities across Asia to share lessons in developing air pollution, climate change, transportation, land-use and energy policies (Clean Air Asia 2017). The C40 Cities Climate Leadership Group is another example, which connects officials in cities to their peers in cities around the world to exchange information as they face common challenges associated with climate change mitigation and adaptation (Day *et al.* 2018).

At both international and local levels, coalitions and initiatives have formed between governments, industry and other groups to facilitate specific actions. The Climate and Clean Air Coalition for Reduction of Short-Lived Climate Pollutants (CCAC) is an example of a coordinated effort to make near-term progress focused on specific pollutants and sectors (CCAC 2015).

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