

Atmosphere



© Walker/Wüthrich

Coordinating lead authors: Johan C.I. Kuypenstierna and May Antoniette Ajero

Lead authors: Drew Shindell, Eric Zusman, Frank Murray, Geir Braathen, Kevin Hicks, Linn Persson, Lisa Emberson, Martha Barata, Sara Feresu, Sara Terry, T.S. Panwar, Yousef Meslmani and Nguyen Thi Kim Oanh

Contributing authors: Luis Abdón Cifuentes, Msafiri Jackson, Nicholas Muller, Paulo Artaxo, Seydi Ababacar Ndiaye, Susan Casper Anenberg and Emily Nyaboke (GEO Fellow)

Principal scientific reviewer: Evgeny Gordov

Chapter coordinator: Volodymyr Demkine

Main Messages

The global atmosphere is at a critical stage, particularly in relation to climate change. There is considerable scientific evidence of the causes and solutions that could protect human health and ecosystems, and effective action has resulted in the achievement of some internationally agreed goals.

The phase-out of ozone-depleting substances and lead in petrol by implementing relatively simple and cost-effective solutions demonstrates that, when most major stakeholders agree, significant progress is possible.

Progress in achieving environmental goals for particulate matter (PM) and tropospheric ozone is mixed, despite the high levels of concern about their impacts, as solutions are complex and can be costly. Much of the developed world has successfully reduced concentrations of indoor and outdoor PM, sulphur and nitrogen compounds to levels close to or within World Health Organization guidelines. However, more remains to be done. Concern is high in Africa, Asia and Latin America, where levels of PM in many cities remain far in excess of the guidelines. Existing solutions can be relatively costly and the time it will take to meet guideline or target concentrations will depend on the priority given to the issue. Tropospheric ozone also remains a significant problem and is proving difficult to address despite some progress with regard to peak concentrations in Europe and North America.

Climate change is the most important atmospheric issue. While there is considerable concern about this complex problem, progress has been slow due to varying levels of motivation and because some low-carbon technological solutions are considered expensive. Despite attempts to develop low-carbon economies in a number of countries, atmospheric concentrations of greenhouse gases continue to increase to levels likely to push global temperatures beyond the internationally agreed limit of 2°C above the pre-industrial average temperature. Application of current low-carbon technologies and existing

policy options would reduce the risks posed by climate change, but a gap of several billion tonnes of carbon dioxide (CO₂) equivalent remains between present emission reduction pledges and those necessary to reach climate targets.

Complementary strategies to address short-lived climate forcers (SLCFs) – black carbon, methane and tropospheric ozone – could, if implemented widely, significantly reduce the rate of temperature increase in the near term while delivering substantial co-benefits for human health and food security. Given that policy tools and technological solutions already exist, progress in reducing SLCFs could be rapid. Nevertheless, this has to be seen as a complementary strategy to the reductions in anthropogenic CO₂ emissions necessary to protect the Earth from exceeding the 2°C limit.

Climate change, air quality and stratospheric ozone depletion are increasingly seen as closely related issues but governments are not addressing them in an integrated manner. An integrated approach to atmospheric protection could support economic development and, by addressing key sectors, policy makers could accomplish multiple goals. Addressing sources of pollution can affect the different gases and particles they emit and deliver multiple climate and air quality benefits. The challenge is to find those solutions that maximize the benefits and lend themselves to widespread implementation.

Investment in achieving atmospheric goals is expected to be cost-effective. The benefits of these policies include reducing anthropogenic radiative forcing, saving millions of lives and significantly enhancing quality of life. Achievement of these benefits and climate and air quality goals requires widespread implementation of currently available technology and proven policy – but it is likely that transformative changes affecting major drivers of emissions are required as well.

INTRODUCTION

Substances emitted to the atmosphere as a result of human activities are a challenge to both the environment and development: millions of people die prematurely each year from indoor and outdoor air pollution; ozone-depleting substances (ODS) have thinned the ozone layer and created seasonal holes in the stratospheric ozone layer over polar regions; and climate change is happening now, and atmospheric concentrations of greenhouse gases and other substances that affect climate continue to increase. Climate change threatens, amongst other things, food security and biodiversity, and it is likely to increase storm damage on all parts of the globe. People in many of the developing regions are especially vulnerable.

These atmospheric issues are addressed by several global and regional agreements including Agenda 21 (UNCED 1992) and the Johannesburg Plan of Implementation (WSSD 2002). Internationally agreed goals and, in some cases, targets have been established. In addition, there are some internationally agreed guidelines related to human health and ecosystems that are used to monitor progress in addressing atmospheric issues.

This chapter uses key indicators to assess progress in relation to goals set at global and regional levels for atmospheric issues. It considers whether progress is on track to achieve these goals using existing policies and measures, and whether they are sufficient to address the key issues important to human well-

being and development. The chapter then considers the outlook for the different issues and what more needs to be done. Where existing policies fall short, the need for more transformative change is highlighted, a concept that is expanded in Chapter 16.

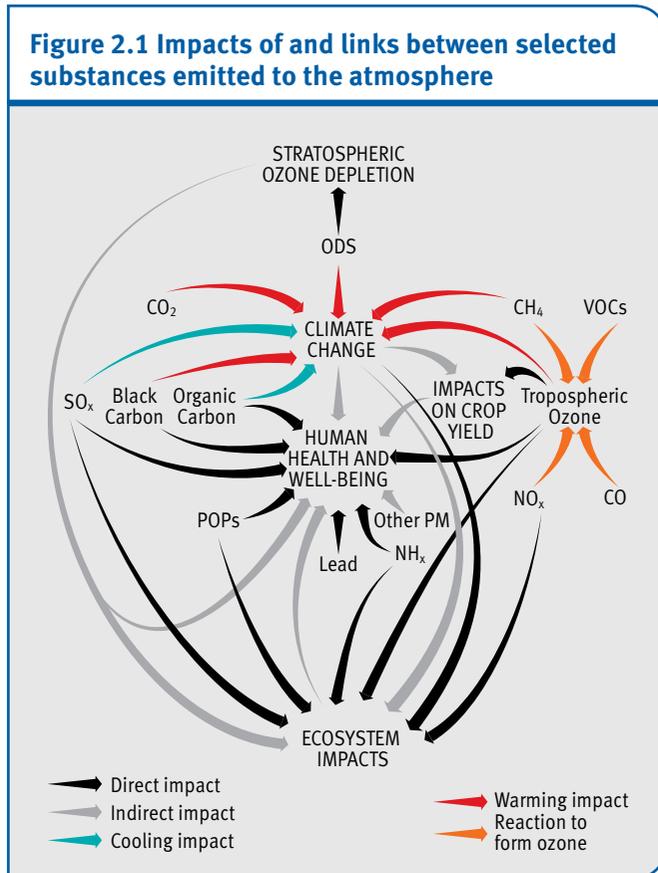
The scientific basis for the development of air pollution policy has greatly improved and there is increasing understanding of the socio-economic aspects of atmospheric issues (Stern 2007). Recently, science has pointed to new challenges such as near-term climate change and short-lived climate forcers (SLCFs) (Shindell *et al.* 2012; UNEP and WMO 2011), and knowledge about thresholds and tipping points has improved (Lenton *et al.* 2008).

Climate change, air quality and stratospheric ozone depletion are closely related, as individual pollutants can have multiple impacts on health, crop yields, ecosystems, cooling or heating of the atmosphere and stratospheric ozone depletion, all with the potential to affect human well-being (Figure 2.1). Many sources also emit multiple pollutants that can both affect air quality and cause climate change. Yet, despite these links, most governments address these issues separately, in part because goals were set in this way 20 years ago. Depending on which measures are implemented, there could be co-beneficial or antagonistic outcomes and, unless a more integrated approach is developed, there is a risk that different atmospheric policies could work against each other.

INTERNATIONAL GOALS AND TARGETS

Major goals to protect the environment and human well-being from the impact of substances emitted to the atmosphere were established in Agenda 21 (UNCED 1992) and the Johannesburg Plan of Implementation (WSSD 2002). These emphasized the need to identify threshold levels of pollutants and greenhouse gases that cause “dangerous anthropogenic interference with the climatic system and environment” (Agenda 21 Chapter 9). Meeting the objectives to phase out chlorofluorocarbons (CFCs) and other ozone-depleting substances – as defined in the 1985 Vienna Convention for the Protection of the Ozone Layer (UNEP 1985) and its 1987 Montreal Protocol on Substances that Deplete the Ozone Layer (UNEP 1987) – was considered essential. These also recognized the importance of the 1979 Convention on Long-Range Transboundary Air Pollution (CLRTAP) and its protocols to reduce regional air pollution, and recommended that these programmes be continued and enhanced, and their experience shared with other regions.

The Johannesburg Plan of Implementation went on to consider air quality as a part of overall development, promoting an integrated approach to policy making. It stressed the need to reduce respiratory diseases and other health impacts resulting from air pollution, paying particular attention to women and children. It supported the phasing out of lead in petrol, measures to prevent children’s exposure to lead, and efforts to strengthen the monitoring, surveillance and treatment of lead poisoning. Another focus was to assist developing countries in providing affordable energy to rural communities, particularly to reduce dependence on traditional fuels for cooking and heating.





Delegates at the 2011 UN Climate Change Conference in Durban, South Africa. © UNFCCC/Jan Golinski

Atmospheric issues are closely linked to the Millennium Development Goals (MDGs) (UN 2000), as shown in Table 2.1. Other non-atmosphere-related conventions such as the 1992 Convention on Biological Diversity (CBD) also have links with the impacts of atmospheric pollution. The Aichi Biodiversity Targets (CBD 2010a) include two atmosphere-related targets:

- Target 8: by 2020, pollution, including from excess nutrients, will have been brought to levels that are not detrimental to ecosystem function and biodiversity; and
- Target 10: by 2015, the multiple anthropogenic pressures on coral reefs, and other vulnerable ecosystems impacted by climate change or ocean acidification will have been minimized, so as to maintain their integrity and functioning.

Atmospheric goals and targets are supported by both legally and non-legally binding environmental agreements (Table 2.2),

most of which contain globally agreed quantitative targets and timelines for implementation that have catalysed the development and implementation of national regulation. The goals and targets refer to different aspects of control, including:

- control of drivers, for example the total ban – with a few exceptions – of the production and consumption of ozone-depleting substances, and the phase-out of leaded petrol;
- reducing pressures, for example emission reductions of carbon dioxide (CO₂) and other greenhouse gases; and
- targeting concentrations of, for example, particulate matter (PM) and CO₂.

For outdoor and indoor air pollution there are no global targets as such, but the World Health Organization (WHO) has established air quality guidelines, based on scientific research,

Table 2.1 Atmospheric issues affecting achievement of the Millennium Development Goals

Goal	Target	Impact
Eradicate extreme poverty and hunger	Halve, between 1990 and 2015, the proportion of people suffering from hunger	Climate variability and change (trends and extremes) affect crop production; tropospheric ozone directly affects crop yields
Achieve universal primary education	Ensure that, by 2015, children everywhere, boys and girls alike, will be able to complete a full course of primary schooling	Lead exposure affects cognitive development and function in young children
Reduce child mortality	Reduce by two-thirds, between 1990 and 2015, the under-five mortality rate	Children are the most susceptible to health impacts of air pollution and lead poisoning; indoor air pollution from cooking with biomass fuels disproportionately affects women and small children
Ensure environmental sustainability	Reduce biodiversity loss, achieving, by 2010, a significant reduction in the rate of loss	Climate change is one of the greatest threats to biodiversity; eutrophication from nitrogen deposition affects the diversity of terrestrial vegetation; tropospheric ozone affects vegetation composition in sensitive ecosystems; ocean acidification and warming affect marine biodiversity

Source: (goals and targets) UN 2000

to help assess progress towards reducing risks from air pollution (WHO 2006). The limit for global temperature increase at the end of the century – the agreed 2°C limit – was set on the basis of scientific discussion of the potential impacts, but also political realities and the likelihood that it could be achieved (Hare *et al.* 2011). Countries set national air-quality standards and even greenhouse gas commitments or targets specific to their international obligations, development situation and institutional capacities. The Copenhagen Accord (UNFCCC 2009) invited developed countries to submit economy-wide emission reduction targets for 2020 and developing countries

to submit nationally appropriate mitigation actions (NAMAs). The Cancun Agreements (UNFCCC 2010) legally recognized these pledged targets and actions, formally anchoring them in the United Nations Framework Convention on Climate Change (UNFCCC). The CLRTAP remains the only regional agreement on transboundary air pollution that sets targets for many different pollutants. Some regions, and sub-regions – Africa, Asia and South America – have cooperation agreements that show intent to reduce emissions, but these are not binding, and in some cases have not been implemented due to lack of human and financial resources.

Table 2.2 Selected internationally agreed goals and themes related to atmospheric issues

Major themes from internationally agreed goals		Numerical target	Coverage
Stratospheric ozone depletion			
Vienna Convention for the Protection of the Ozone Layer (UNEP 1985)	Protect the ozone layer		Global
Montreal Protocol on Substances that Deplete the Ozone Layer (UNEP 1987)	Eliminate ozone-depleting substances	Zero production and consumption of ozone-depleting substances, with stated exceptions	Global
Climate change			
United Nations Framework Convention on Climate Change (UNFCCC 1992)	Stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system		Global
Kyoto Protocol to the UNFCCC (UNFCCC 1998)	Reduce greenhouse gas emissions from industrialized countries	At least 5% reduction in emissions from Annex 1 (developed) countries by 2012 compared to 1990; specific national reduction commitments	Annex 1 countries
Cancun Agreements (UNFCCC 2010)	Reduce global emissions to limit the global average temperature increase to 2°C above pre-industrial levels	Quantified economy-wide emission pledges for 2020 for Annex 1 Parties and nationally appropriate mitigation actions for non-Annex 1 Parties (developing countries)	Global
EU 20-20-20 targets (EEA 2009)	Reduce greenhouse gas emissions from EU countries by 2020	20% reduction in emissions from 1990 levels; 20% energy consumption to come from renewable sources; 20% cut in primary energy use compared to projected levels	EU Member States
Lead pollution			
Agenda 21 (UNCED 1992); Johannesburg Plan of Implementation (WSSD 2002)	Prevent exposure to lead	Zero emission of lead from transport	Global
Air quality for health and ecosystems			
WHO guidelines (WHO 2006)	Reduce the health effects of air pollution	Guidelines set for PM _{2.5} , PM ₁₀ , SO ₂ , NO ₂ , Pb, CO and O ₃ , e.g. PM _{2.5} – 10 µg per m ³ annual mean; PM ₁₀ – 20 µg per m ³ annual mean WHO guidelines for ecosystems set on the basis of critical levels and loads as set for CLRTAP	Globally recommended
Air pollution			
EU directives for air quality, vehicles, stationary sources and national emissions (EC 2008)	Improve human health and environmental quality up to 2020	Guidelines set for PM _{2.5} , PM ₁₀ , SO ₂ , NO ₂ , Pb, CO and O ₃ , e.g. PM _{2.5} – 25 µg per m ³ annual mean, PM ₁₀ – 40 µg per m ³ annual mean; critical loads and levels also set for ecosystems; national emissions ceilings set for each EU country for SO ₂ , NO _x , VOC and NH ₃	EU Member States
Transboundary air pollution			
Convention on Long-Range Transboundary Air Pollution (CLRTAP) (UNECE 1979)	Protect humans and the environment from air pollution, to be implemented through objectives set in the convention protocols	The Gothenburg Protocol (UNECE 2005) sets reductions for all Parties – a multi-pollutant/multi-effect protocol with reduction targets for emissions compared to 1990 to be achieved in 2010 (being revised with 2020 targets): refer to Annex II of the protocol for specific country emission ceilings	UNECE countries of Europe, Central Asia and North America
ASEAN Haze Agreement (ASEAN 2002)	Monitor and prevent transboundary haze pollution as a result of land and/or forest fires	Agreed to adopt the policy of zero burning	ASEAN countries of South East Asia

PROGRESS IN ACHIEVING ATMOSPHERIC GOALS

This section examines progress in addressing concerns about the atmosphere over the 20 years or so since Agenda 21 (UNCED 1992) identified key priorities. The goals and targets set globally and regionally for a number of atmospheric issues are compared to the current situation, examining whether they have been met and determining the size of the gap between the current situation and the goals and targets.

Progress is described against key indicators by considering atmospheric issues in three main categories:

- examples of where targets are not being met and the situation remains far from sustainable;
- examples of mixed progress, with some regions having met targets and others remaining far from them; and
- examples of good progress, where targets have been set and are largely met.

Climate change: goals far from being met

There is broad scientific consensus that anthropogenic emissions of CO₂ and other greenhouse gases are the leading cause of contemporary climatic changes (IPCC 2007). Four independent analyses show that 2000–2009 was the warmest decade on record with atmospheric concentrations of CO₂ also increasing (Figure 2.2). A look at regional temperature changes shows that the greatest warming over the past century is at high latitudes (Figure 2.3).

Climate change threatens human well-being in many ways, from a greater frequency of heat waves and severe storms, to shifts in rainfall patterns and rising sea levels (IPCC 2007). Changes in the frequency of tropical cyclones are uncertain, but it is likely that their intensity will increase with rising temperatures (IPCC 2011).

Humans are directly affected, for example through alterations in freshwater supply, agricultural productivity and health, and indirectly by the economic and social impacts of loss of biodiversity and ecosystem services. Climate change is therefore considered to be the most significant problem related to changes in the atmosphere being faced by humankind. A review of the



More than 22 000 homes were inundated in the disastrous Brisbane Flood of 2011, the worst flood in Australia's history. © On-Air/iStock

Box 2.1 Climate change

Related goals

Prevent dangerous anthropogenic interference with the climate system (UNFCCC)

Indicators

Temperature trends; rainfall changes; sea ice extent; CO₂ concentrations; greenhouse gas emissions

Global trends

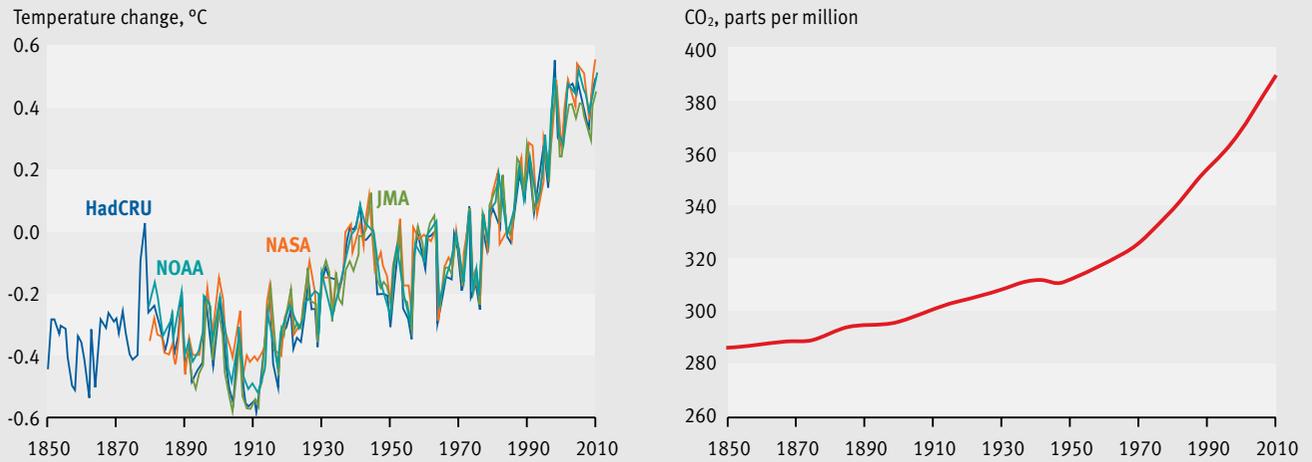
Slow progress; not on track to avoid crossing UNFCCC's agreed temperature rise limit of 2°C

economics literature suggests that damage from climate impacts could amount annually to 1–2 per cent of world gross domestic product (GDP) by 2100 if temperatures increase by 2.5°C above pre-industrial levels. These damage estimates rise to 2–4 per cent of world GDP for a 4°C increase (Aldy *et al.* 2010). The few studies that estimate damages for extreme warming find that annual losses to world GDP by 2100 could range from 10.2 per cent for a 6°C warming increase (Nordhaus and Boyer 2000) to 11.3 per cent for a 7.4°C warming increase (Stern 2007). While valuation is sensitive to underlying assumptions about discount rates and catastrophic effects, it is clear that the socio-economic impacts of climate change are likely to be very large.

Impacts will probably be especially significant in the Arctic where warming is likely to be the greatest. Large portions of the Arctic have experienced temperature increases of more than 2°C compared to 1890–1910 (Figure 2.3), and Arctic sea ice cover has decreased dramatically, with declines in both the autumn and the winter (Figure 2.4). The Greenland and Antarctic ice sheets both show rapidly increasing melt rates and the Greenland melt area has expanded markedly (Rignot *et al.* 2011). Other areas where sizeable climate change impacts are projected include the sub-tropics, where arid regions are expected to expand, and low-lying areas, where sea-level rise is likely to cause the most damage. Less developed countries that have limited capacity to adapt to these changes are at risk of not meeting their development goals.

Extreme weather events are expected to change in frequency and intensity, becoming more common as the climate warms, including regional heat waves and both wet and dry extremes of precipitation (IPCC 2007). Europe experienced two extremely hot summers in 2003 and 2010, and research shows that the probability of extreme summer heat, including mega-heat waves, will increase by a factor of 5–10 within the next 40 years (Barriopedro *et al.* 2011). The frequency of heavy precipitation events has increased over most of the world's land area (Chapter 4), and more intense and longer droughts have been observed since the 1970s, particularly in the tropics and sub-tropics (IPCC 2007). Long-term trends show a tendency towards drier conditions in the Sahel and northern India (Figure 2.5).

Figure 2.2 Trends in temperature change and atmospheric CO₂ concentrations, 1850–2010



Note: 0 = 1961–1990 global mean

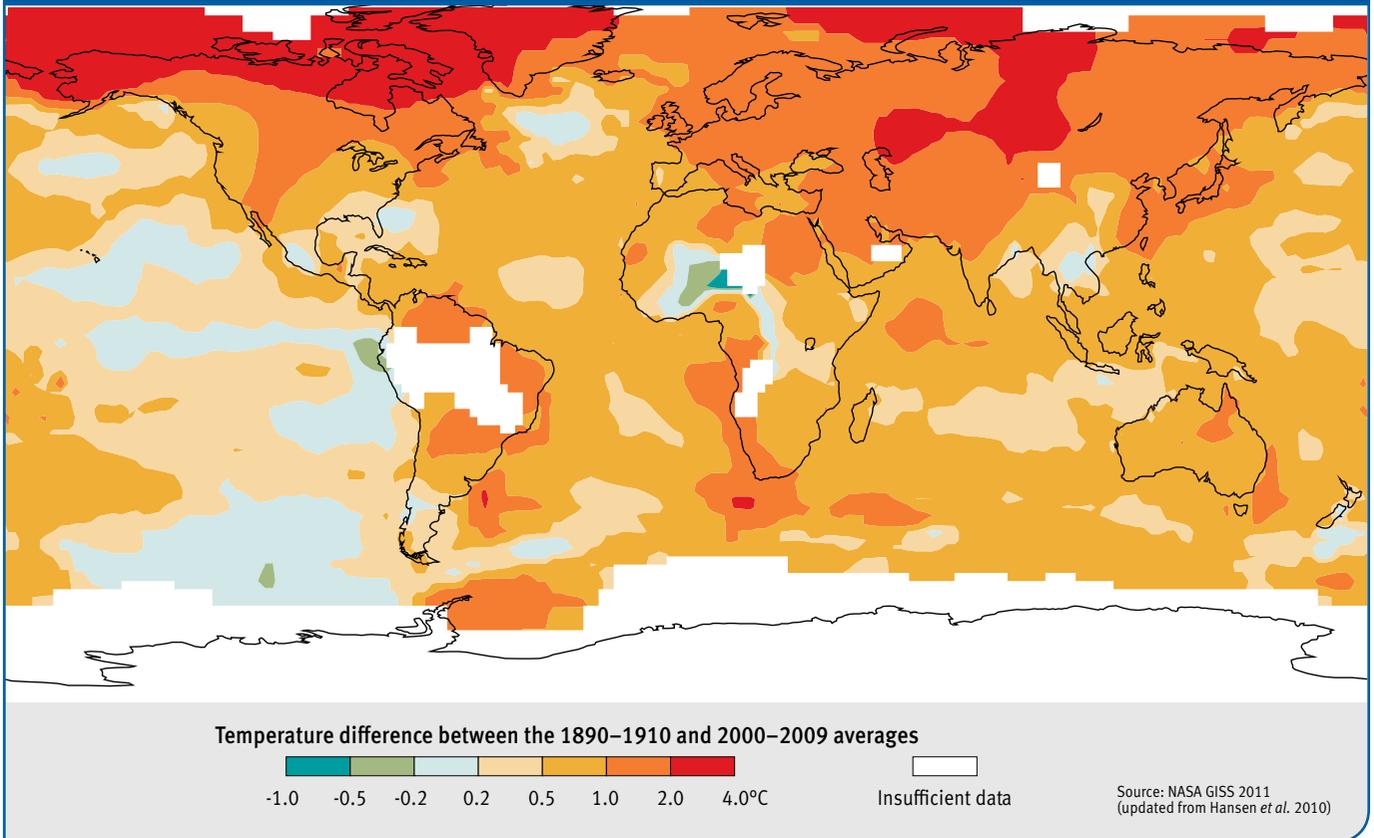
Source: NOAA NCDC; NASA GISS; Hadley Climatic Research Unit at the University of East Anglia (HadCRU); Japan Meteorological Agency (JMA)

Source: Scripps Institute of Oceanography, NOAA

There is growing concern that inaction will lead to changes that are irreversible at human timescales – so-called tipping points. Increased release of carbon stored in permafrost, as CO₂ or

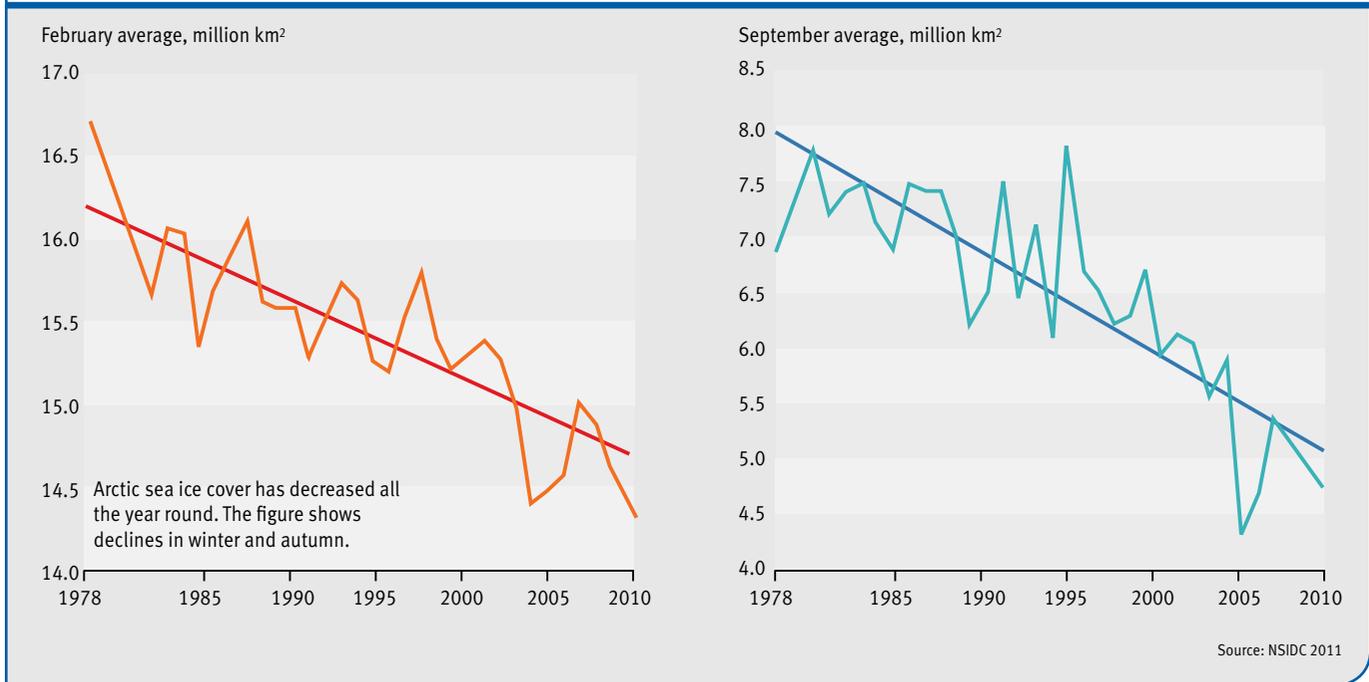
methane, is an example of a change that could give rise to a cycle of further warming and further releases of greenhouse gases (Schaefer *et al.* 2011; Lawrence and Slater 2005).

Figure 2.3 Temperature change over the 20th century



Source: NASA GISS 2011 (updated from Hansen *et al.* 2010)

Figure 2.4 Trends in Arctic sea ice extent in winter and autumn, 1979–2010



Concentrations and emissions of most anthropogenic greenhouse gases have increased during recent years (Table 2.3 and Figure 2.6). Growth rates have been especially high for concentrations of several hydrofluorocarbons (HFCs) while emissions of CO₂ from fossil fuel consumption have followed the more pessimistic of the widely used projections

of the Intergovernmental Panel on Climate Change *Special Report on Emission Scenarios* (SRES) (IPCC 2000) during the last decade, despite a brief downturn in global emissions in 2009 associated with the economic recession (Figure 2.6). The rapid growth of CO₂ concentrations is also associated with similarly rapid increases in ocean acidification (Chapter 4).

To avoid exceeding the 450 ppm atmospheric concentrations of CO₂-equivalent that are likely to be required to stay within the temperature rise limit of 2°C, the IPCC has concluded that developed countries need to reduce emissions by 25–40 per cent below 1990 levels by 2020 (IPCC 2007), while peer-reviewed

Figure 2.5 Trends in African and South and West Asian rainfall, May–September, 1960–1998

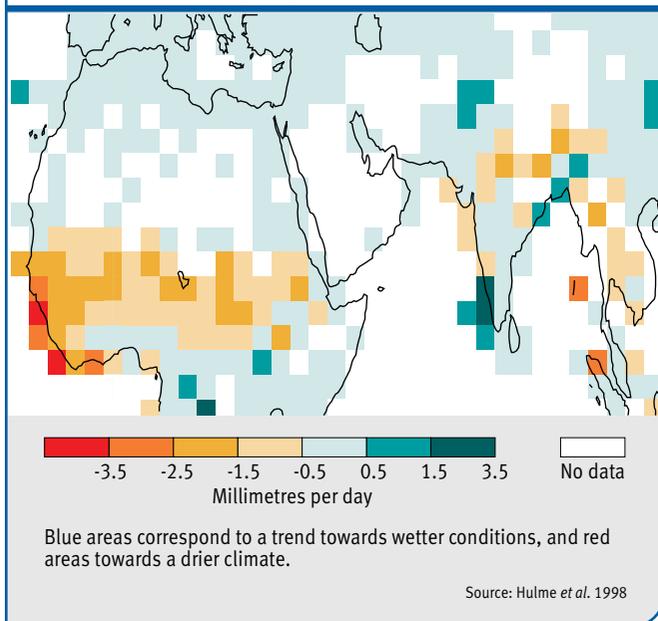
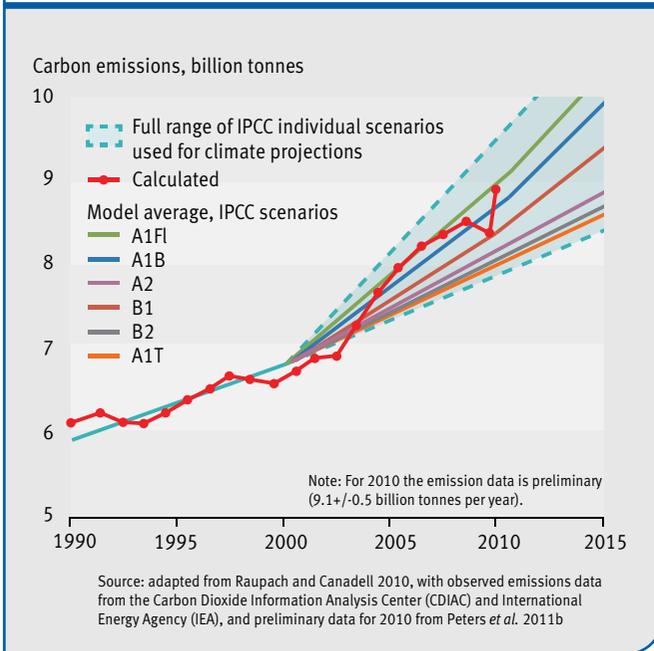


Table 2.3 Concentrations of greenhouse gases, 2005, 2009 and 2010

	2005	2009	2010
CO ₂ (ppm)	378.7	386.3	388.5
CH ₄ (ppb)	1 774.5	1 794.2	1 799.1
N ₂ O (ppb)	319.2	322.5	323.1
CFC-11 (ppt)	251.5	243.1	240.5
CFC-12 (ppt)	541.5	532.6	530.8
HCFC-22 (ppt)	168.3	198.4	206.2
HFC-134a (ppt)	34.4	52.4	57.8

Source: NOAA GMD 2011a

Figure 2.6 Trends in fossil fuel emissions, calculated and IPCC scenarios, 1990–2015



literature has concluded that developing countries need to reduce emissions by 15–30 per cent relative to business-as-

usual by 2020 (den Elzen and Höhne 2010, 2008). Further reductions are then required beyond 2020 to achieve the target. While some countries have reduced CO₂ emissions since the Kyoto Protocol entered into force in 2005, many appear unlikely to reach their Kyoto targets. Further, many of the same countries reporting reductions have increased imports of carbon-intensive products – so-called carbon leakage. Accounting for the foreign CO₂ emissions embedded within imported products, emissions have in fact increased in many developed nations and the net domestic-plus-embedded emissions are far greater than the Kyoto targets (Peters *et al.* 2011a).

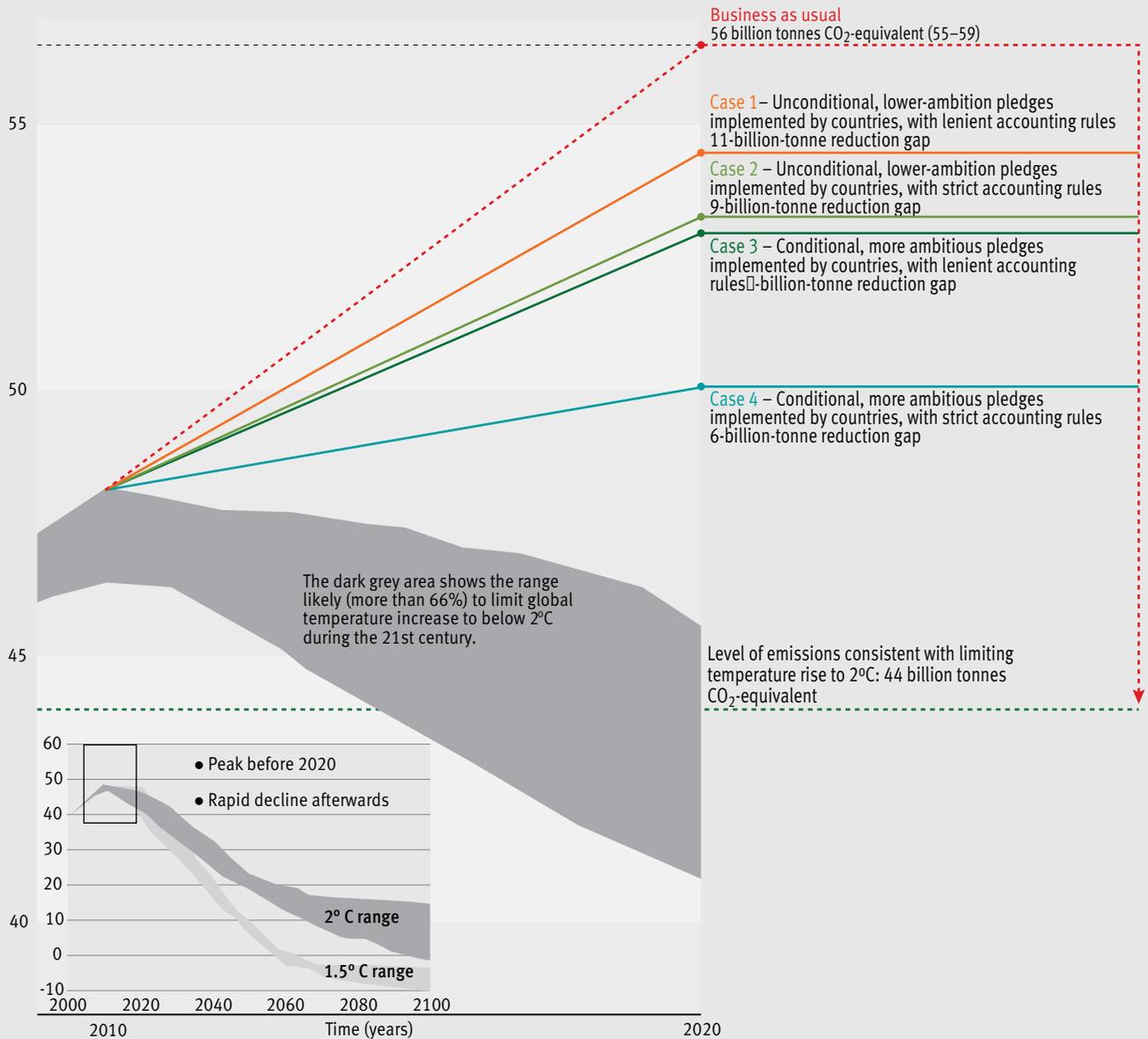
The years since the Bali Action Plan (UNFCCC 2008) have seen 42 developed countries pledge quantified economy-wide emission targets up to 2020, while 44 developing countries have pledged nationally appropriate mitigation actions. Nonetheless, these commitments fall short – by about 6 billion tonnes of CO₂-equivalent – of levels likely to keep temperatures within safe limits as shown in Figure 2.7. This figure compares the expected emissions in 2020, resulting from four possible interpretations of pledges of mitigation action from 86 countries, with the range of emission levels that would provide a greater than 66 per cent chance of staying below the agreed 2°C temperature rise limit. The gap between expected emissions and the agreed UNFCCC 2°C limit lies between 6 billion and 11 billion tonnes of CO₂-equivalent. The size of the gap depends on the extent to which the pledges are implemented and how they are applied (UNEP 2011a).



Addressing sources of pollution can deliver both climate and air quality benefits. © Morten Madsen/iStock

Figure 2.7 The emissions gap

Annual emissions, billion tonnes CO₂-equivalent



A comparison of the gap between expected emissions in 2020 according to submitted country pledges, formally recognized in Cancun, and the range of emissions likely to limit temperature increase to the agreed UNFCCC 2°C limit.

Source: UNEP 2011a

An historical tendency to underestimate rates of climate change suggests that non-linear changes and material losses at the higher end of estimated ranges are also possible (Smith *et al.* 2009; Stern 2007). Overall, prospects for long-term climate change look bleak if there is no demonstrable progress at both international and national levels.

Even if negotiations take longer than expected at the international level, national actions should continue to move

forward. A growing body of low-carbon research has shown that in countries ranging from the United Kingdom (Strachan *et al.* 2008) and Japan (Fujino *et al.* 2008) to Thailand (Shrestha *et al.* 2008), it would be economically and technically feasible to cut emissions in half by 2050. The results of these studies are based on placing a price on carbon through, for instance, an emissions trading scheme. It is important to note, however, that market-based instruments such as emissions trading schemes or the Clean Development Mechanism (CDM) may not work in all



The boom in global trade has led to significant emissions of CO₂ and key pollutants including SO₂, NO_x and black carbon from international shipping. © Mark Wragg/iStock

contexts or benefit all regions equally. For example, in the CDM market, Latin America and Asia and the Pacific account for more than 87 per cent of all projects while Africa accounts for less than 3 per cent (UNFCCC 2012).

Other studies suggest that mainstreaming climate change into existing development plans could provide a more promising alternative to market-based instruments, especially for those developing countries that constrain their development with an emissions cap (Shukla *et al.* 2008). This is reinforced by research that shows that because of the relatively greater value of co-benefits, such as improved local air quality, low-income countries have the most to gain from mitigating greenhouse gases in a manner consistent with development priorities (Nemet *et al.* 2010). Capturing these co-benefits not only requires that policy makers become adept at mainstreaming climate change in development plans, but also necessitates decision-making frameworks that explicitly acknowledge synergies between climate change and other atmospheric issues. Such an integrated approach can readily be put in place at local and city levels, where a considerable amount of climate mitigation and air quality control has already been implemented.

Mixed progress

There are examples of improvement in some regions while large difficulties remain in many others, and global targets are still far from being met. Four major atmospheric issues are described below: sulphur, nitrogen, small particulate matter (typically described as PM₁₀ and PM_{2.5}) and tropospheric ozone.

Sulphur pollution

Sulphur dioxide (SO₂) emissions, predominantly from fossil fuel use in power generation, industry and transport, have detrimental effects on human health by contributing to PM_{2.5}, on terrestrial and freshwater ecosystems by acidification (Rodhe *et al.* 1995), on man-made materials and cultural heritage by corrosion (Kucera *et al.* 2007), and on biodiversity (Bobbink *et al.* 1998) and forestry (Menz and Seip 2004). Sulphate aerosols also cool the atmosphere (Forster *et al.* 2007), which makes it important to track them in order to assess the overall benefits of greenhouse gas reduction strategies.

Since issues of transboundary air pollution were highlighted in Agenda 21 (UNCED 1992) there have been considerable

Box 2.2 Sulphur pollution

Related goals

CLRTAP, EU Directives and WHO guidelines for human health and ecosystems

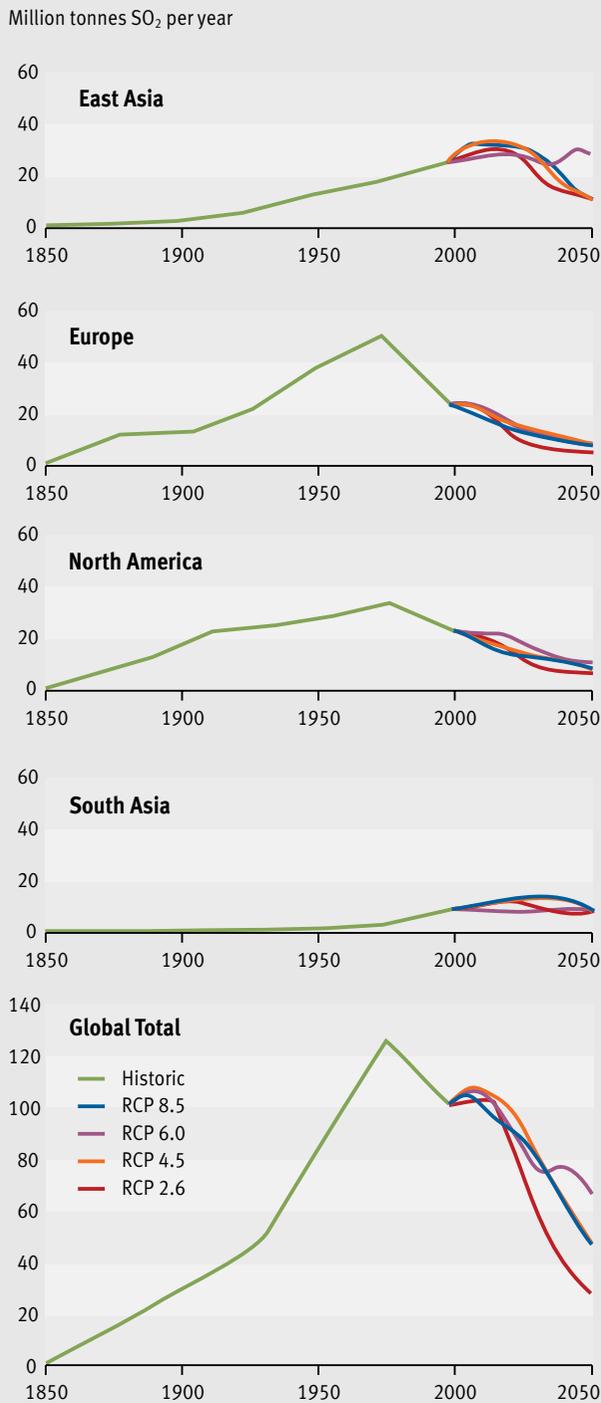
Indicators

Sulphur emissions; exceedance of critical loads/levels (thresholds above which harmful effects are observed)

Global trends

Mixed regional progress

Figure 2.8 Regional trends in sulphur dioxide emissions, 1850–2050



Emission trends from 1850–2000 and four Representative Concentration Pathway (RCP) scenarios from 2000–2050, developed to contribute to the Fifth Assessment of the IPCC, are shown for the four source regions and for the global total from the hemispheric transport of air pollution (HTAP) multi-model experiments.

Source: HTAP 2010

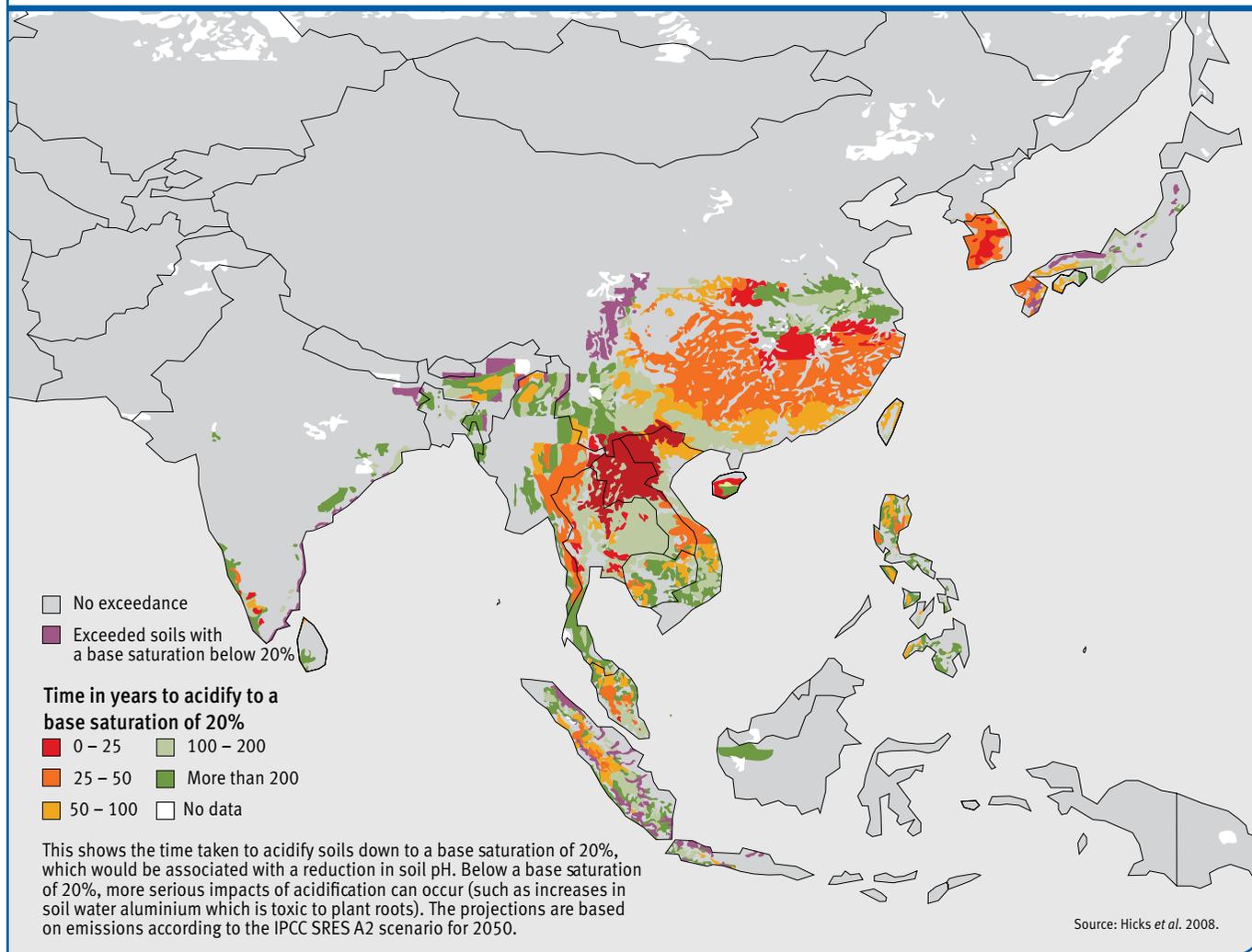
reductions in sulphur dioxide emissions in Europe and North America, achieving the targets of the CLRTAP protocols, the National Emission Ceiling (NEC) Directives of the European Union (EU) and clean air legislation in Canada and the United States (Figure 2.8). Key to the development of country targets in Europe was the use of critical loads (deposition thresholds above which harmful effects are observed) (Nilsson and Grennfelt 1988). Successful implementation of legislation brought about a drop of around 20 per cent in global emissions between 1980 and 2000. Emissions from Europe and North America were dominant until about 2000, when East Asian emissions started to dominate. According to the Representative Concentration Pathway (RCP) scenarios (Figure 2.8), global sulphur dioxide emissions were projected to decline steadily after 2005, and by 2050 to be 30, 50 or 70 per cent lower than 2000 levels. This set of four new pathways was developed for the climate modelling community as a basis for near- and long-term modelling experiments (van Vuuren *et al.* 2011; Moss *et al.* 2010).

As sulphur deposition has abated in Europe and North America, acidification has also diminished and some freshwater ecosystems have recovered, although critical loads are still exceeded in some areas (Wright *et al.* 2005; Stoddard *et al.* 1999). In Asia, the increase in emissions has put sensitive ecosystems at risk from the effects of soil acidification (Figure 2.9). However, the large-scale acidification of natural lakes experienced in Europe and North America has not been seen in Asia, and may be unlikely due to the nature of the region's soil and geology (Hicks *et al.* 2008). In 2005 it was estimated that the critical load for soils in China was exceeded by sulphur deposition across 28 per cent of the country's territory, mainly in eastern and south-central China. The area in exceedance is projected to decrease to 20 per cent in 2020, given the implementation of current plans for emission reductions (Zhao *et al.* 2009).

Further action on sulphur emissions is being taken through the revision of the Gothenburg Protocol in Europe. In Asia, action is also being taken to improve the efficiency of energy use and reduce sulphur dioxide emissions. For example, as part of its five-year plans, China implemented flue-gas desulphurization and the phasing out of small, inefficient units in the power sector in a move to achieve the national goal of a 10 per cent reduction in sulphur dioxide emissions between 2005 and 2010 (Zhang 2010).

Global efforts are also being made to reduce sulphur emissions from key sectors, including transport and shipping. The human health effects of particulate matter measuring 2.5 micrometres or less in diameter (PM_{2.5}) are being tackled by lowering the sulphur content of diesel fuels – for example, UNEP's Partnership for Clean Fuels and Vehicles (PCFV) is promoting the reduction of sulphur in vehicle fuels to 50ppm or below worldwide (UNEP 2012). Sulphur emissions from shipping have become an important policy issue in Europe, while the International Convention for the Prevention of Marine Pollution from Ships (MARPOL) is committed to the progressive global reduction in

Figure 2.9 Areas at risk and timeframe for acidification damage in Asia



emissions of sulphur oxides, nitrogen oxides and particulate matter (MARPOL 2011 Annex VI).

Nitrogen compounds

Human activity linked to energy use and food production has more than doubled the amount of reactive nitrogen circulating in the environment over the past century (ENA 2011). This is emitted to the atmosphere as nitrogen oxides (NO_x), mainly from the transport and industry sectors, and ammonia (NH₃) and nitrous oxide (N₂O), mainly from agriculture. They have multiple effects on the atmosphere, terrestrial ecosystems, freshwater and marine systems, and on human health, a phenomenon known as the nitrogen cascade (Galloway *et al.* 2003). Nitrogen compounds are precursors of atmospheric PM_{2.5}, which has impacts on human health, while nitrogen oxide is a precursor of tropospheric ozone, which has impacts on health, crop yields, ecosystems and climate. Nitrous oxide and tropospheric ozone are also important greenhouse gases. Nitrogen deposition drives biodiversity loss through eutrophication and acidification in terrestrial and aquatic ecosystems (Bobbink *et al.* 1998). However, it can also be of

benefit to crop yields, and can increase carbon sequestration through the stimulation of forest growth (ENA 2011).

Box 2.3 Atmospheric nitrogen pollution

Related goals

CBD, CLRTAP, EU directives and WHO guidelines for human health and ecosystems

Indicators

Nitrogen oxides and ammonia emissions; nitrogen deposition; exceedance of critical loads/levels – thresholds above which harmful effects are observed

Global trends

Mixed: reductions in nitrogen oxides in some regions; ammonia emissions set to increase in all regions



Deposition of reactive nitrogen compounds from agriculture, transport and industrial sources can lead to increased emissions of nitrous oxide (N₂O) and loss of biodiversity from ecosystems such as forests. © Orchidpoet/iStock

Total global nitrogen oxide emissions increased until around 2000, but were expected to remain more or less constant thereafter, with reductions in Europe and North America compensating for the growth in emissions in Asia and all other regions (Figure 2.10). Control measures in Europe – where road transport accounted for 40 per cent of emissions in 2005 – succeeded in reducing total nitrogen oxide emissions by 32 per cent between 1990 and 2005 (Vestreng *et al.* 2009), while measures in the United States reduced emissions by 36 per cent between 1990 and 2008 (IJC 2010). In Asia, emissions have continued to increase over the past two decades, with the growth rate itself accelerating during this period (Figure 2.10). Emissions from international shipping are estimated to have risen from 16 million tonnes in 2000 to 20 million tonnes of nitrogen dioxide (NO₂) in 2007 (IMO 2009).

Global ammonia emissions, largely from the agricultural sector, have increased fivefold since the middle of the last century and are projected to continue to climb in all regions with the possible exception of Europe, where they have decreased slightly and may stabilize (Figure 2.10) (EEA 2009). Nevertheless, there is a lack of concern and focus on this issue in Europe, and there is often resistance to major changes from the farming community. In most other regions ammonia is not regulated under major emission control laws. However, the Gothenburg Protocol of CLRTAP is being revised with more stringent targets and is likely to lead to a further reduction in emissions in Europe.

Despite these improvements, nitrogen-based air pollution from agriculture, industry and traffic in urban areas contributes significantly to PM_{2.5} concentrations as secondary nitrate and ammonium particles, which are reducing people's life expectancy by several months across much of Central Europe (ENA 2011).

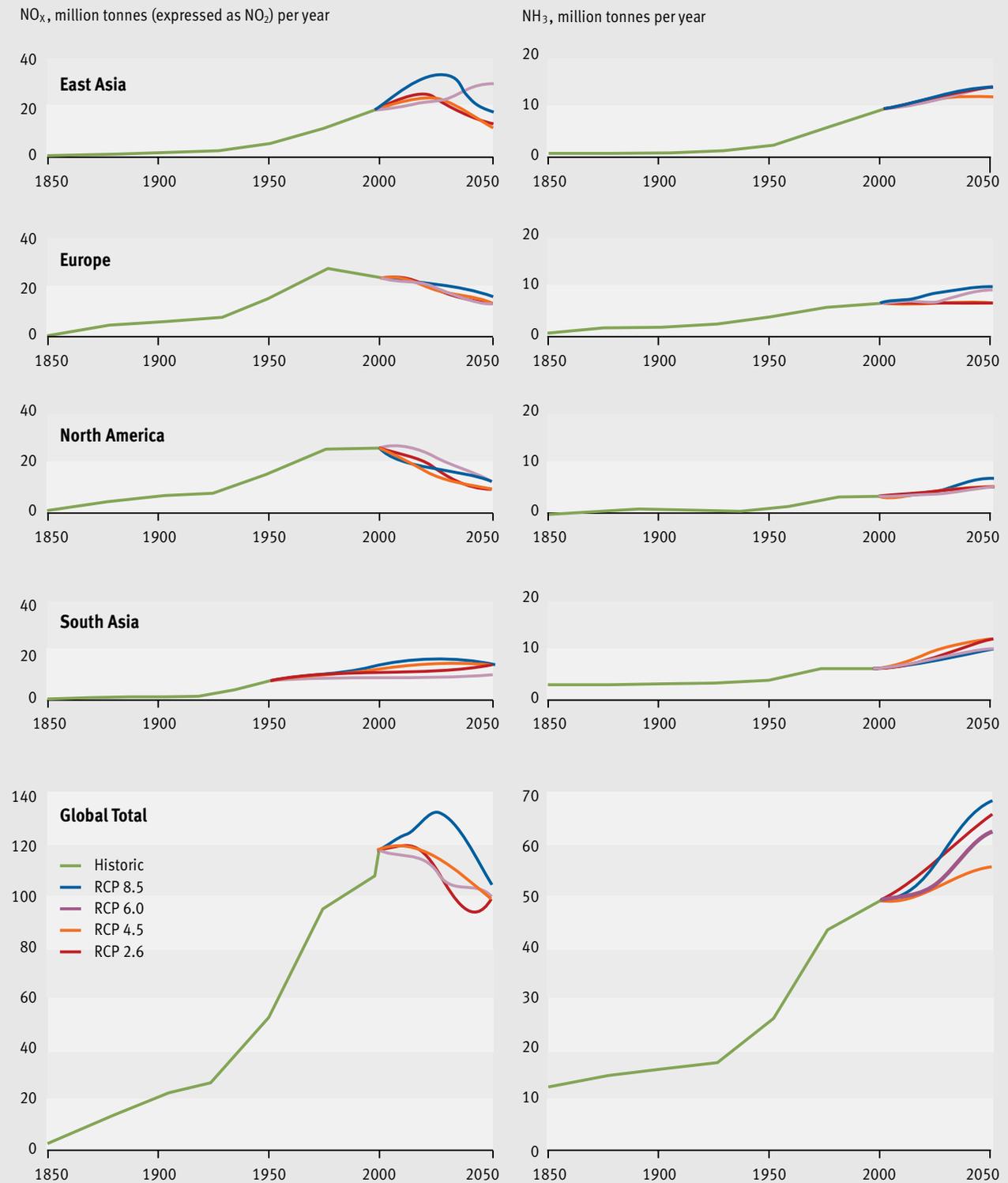
In Africa, Asia and Latin America, where control of nitrogen emissions is not a high priority, projections show increases in emissions of both nitrogen oxides and ammonia (Figure 2.10). In some regions, especially in Africa, lack of monitoring capacity is a major issue. To address this, more policy emphasis on these substances in these regions will be required, especially with regard to emissions from the agricultural, energy, industrial and transport sectors, while ensuring that there is adequate nitrogen fertilizer available for food production.

Current technology can deliver significant reductions in emissions of nitrogen oxide, but growth in certain sectors, particularly transport, can counteract control measures. Changed management practices will be needed to reduce ammonia emissions, and more fundamental consideration of agricultural policy and practice, as well as changes in consumption patterns of meat and dairy products, are required if large reductions are to be achieved.

Rising atmospheric nitrogen deposition will lead to environmental effects associated with the nitrogen cascade (Galloway *et al.* 2003), including impacts on plant diversity. The Convention on Biological Diversity has recognized nitrogen deposition as an indicator of the threat to biodiversity (CBD 2010b) and especially to sensitive ecosystems that receive a total nitrogen deposition above 10 kg per hectare per year (Figure 2.11). However, the full impact is difficult to estimate as there is little quantification of the effects on biodiversity outside Europe and North America.

Designing effective policies to balance the positive impacts of nitrogen deposition, such as increases in crop yields and carbon sequestration, and the negative impacts, such as loss of biodiversity and increased greenhouse gas emissions, underlines the necessity for a truly integrated approach to nitrogen management in the environment.

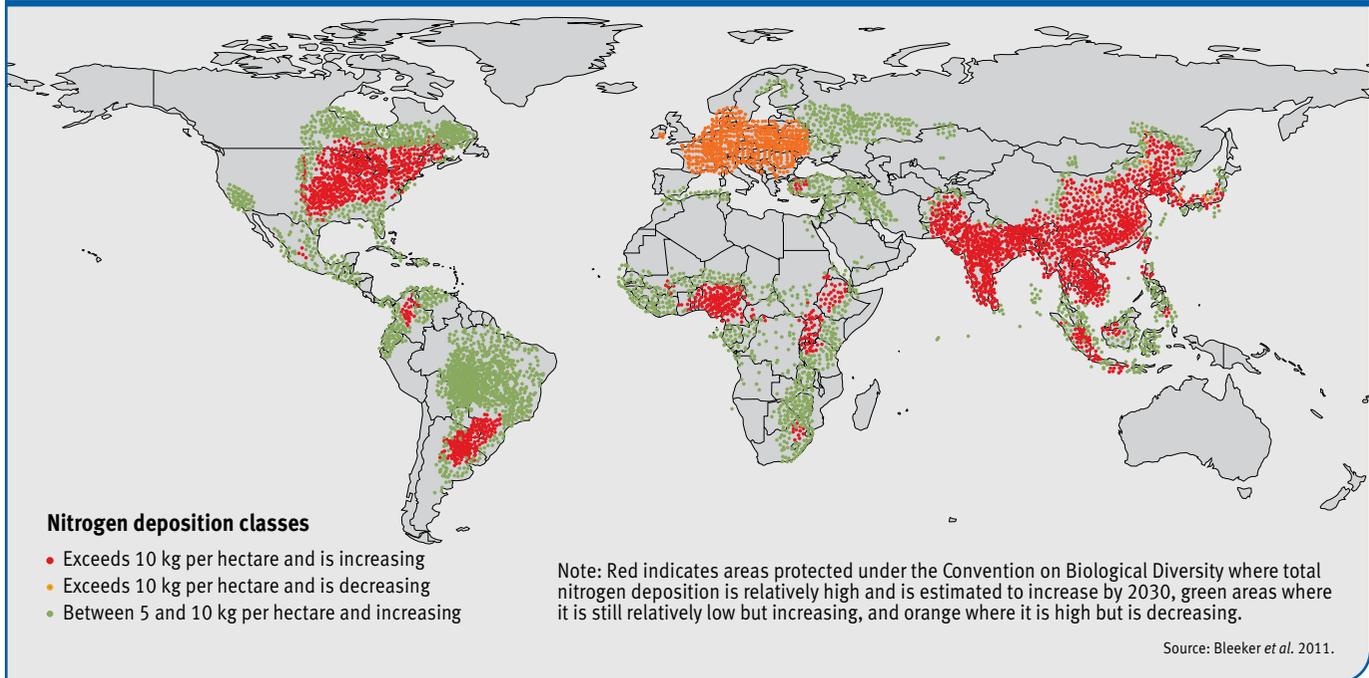
Figure 2.10 Regional trends in emissions of nitrogen oxides and ammonia, 1850–2050



Emission trends from 1850–2000 and four RCP scenarios from 2000–2050, developed to contribute to the Fifth Assessment of the IPCC, are shown for the four regions and for the global total from the HTAP multi-model experiments. Total nitrogen oxide emissions (left) remain more or less constant at global scale while global ammonia emissions (right) are projected to increase in most scenarios.

Source: HTAP 2010

Figure 2.11 Trends in nitrogen deposition to protected areas, 2000–2030



Particulate matter

Control of particulate matter has achieved mixed progress worldwide. In Europe and North America, as well as some cities in Latin America and Asia, emissions of PM_{10} – particles of 10 micrometres in diameter or less – have been reduced, but they remain a major pollutant in many other cities in Asia and Latin America. Very few cities in Africa monitor air pollutants; however, of the few that do, many show PM_{10} concentrations in excess of WHO guidelines (WHO 2012). Outdoor concentrations in high-income countries come close to the WHO PM_{10} guideline of 20 micrograms per m^3 (Figure 2.12). In Africa, the most widespread issue is indoor levels of particulates. Regulating these pollutants is complex because they are composed of a variable mix

of primary emissions and secondary pollutants, where the original emissions are transformed in the atmosphere. An additional challenge for cities is the elimination of particulate hotspots.

Particulate matter, especially the finer $PM_{2.5}$, is the most important air pollutant causing damage to human health (WHO 2011; Carnelley and Le 2001). The prime sources of particulate matter relate to the energy, transport and industry sectors, but open burning of solid waste and crop residues are also important sources. Health research worldwide has shown that there is no safe threshold for exposure, as even very low levels cause health damage (WHO 2006, 1999). Impacts on health are predominantly associated with respiratory and cardiovascular illnesses, but the range of effects is broad for both acute and chronic exposure. Based on exposures to particulate matter in 2004, WHO estimated that annually 5.3 per cent of premature deaths worldwide, about 3.1 million people, are attributable to air pollution – 2 per cent to outdoor urban pollution and 3.3 per cent to indoor pollution – which is more than from all other environmental risks combined (Table 2.4) (WHO 2009). However, a more recent study estimated 3.7 million premature deaths due to outdoor anthropogenic $PM_{2.5}$ alone, as it used a different method that includes exposure in rural areas, does not have a low-concentration threshold, and used updated concentration-response relationships (Annenberg *et al.* 2010). Worldwide, approximately 41 million disability-adjusted life years (DALYs) – the sum of potential healthy life years lost due to illness – are attributed to solid fuel and methods use with about 18 million, or 44 per cent of the total, occurring in sub-Saharan Africa (UNDP and WHO 2009). Household energy

Box 2.4 Particulate matter

Related goals

Protect human health

Indicators

PM levels

Global trends

Mixed progress in relation to WHO guidelines, with significant reductions in the EU and North America and some Latin American and Asian cities, but mostly high concentrations in urban areas in Asia and Latin America; data for Africa is insufficient, but some cities have high PM levels

Table 2.4 Global burden of disease due to particulate air pollution

Air pollution type	Premature deaths	Morbidity (DALYs)
Urban outdoor	1.15 million = 2.0% of deaths worldwide 0.61 million males and 0.54 million females 8% of lung cancer deaths 5% of cardiopulmonary deaths 3% of respiratory infection deaths	8.7 million DALYs
Indoor	1.97 million = 3.3% of deaths worldwide 0.89 million males and 1.08 million females 21% of lower respiratory infection deaths 35% of chronic obstructive pulmonary deaths 3% of lung cancer deaths 0.9 million deaths due to pneumonia among children younger than five years	41 million DALYs
Total air pollution	3.12 million = 5.3% of deaths worldwide	49.7 million DALYs

Note: DALYs – disability adjusted life years: the sum of potential healthy life years lost due to illness.

Source: WHO 2009

interventions, which reduce dependence on traditional fuels and methods for cooking and heating, clearly have the potential to improve health and promote achievement of the MDGs. Even in high-income countries such as the United Kingdom, PM_{2.5} is estimated to have contributed to 29 000 premature deaths and the loss of 340 000 life-years in 2008 (COMEAP 2010), despite considerable progress in reducing concentrations.

Recent assessments of the long-range transport of air pollution indicate that intercontinental transport of particulate matter is contributing to exceedances of public health standards and visibility targets. Long-range transport of particulates may be responsible for 380 000 premature deaths worldwide, of which 75 per cent are attributable to (mineral) dust PM_{2.5} (HTAP 2010). The impacts of air pollution from natural sources are an emerging atmospheric issue requiring attention, and will be discussed in the subsequent section on atmospheric governance.

Various measures, including technological improvements to vehicles, increased transport and energy efficiencies and cleaner fuels and filters, have been successful in developed countries and to some extent in developing ones. However, while the latter are catching up in the use of cleaner technologies, such efficiencies are being compromised by a rapid increase in emission sources, for example fuel use for energy and transport. Where indoor particulates are concerned, global partnerships are promoting cleaner energy and improved cooking stoves.

Most developed and developing countries have adopted ambient air quality standards (Figure 2.12), but concentrations of particulates in most cities exceed the levels recommended by WHO's ambient air quality guidelines for protecting human health and ecosystems (Figure 2.13). Most of the PM₁₀ standards in developing countries are less stringent than the interim targets set by WHO to promote a progressive reduction in air pollution. WHO has also recommended PM_{2.5} guidelines, but many countries have yet to adopt standards and monitoring practices. In Asia in 2010, for example, only four out of the 22 countries have standards for

PM_{2.5} supported by monitoring. There is growing interest in the health impacts of micrometre and sub-micrometre particles, as discussed below in the section on emerging issues.

Projections of a 20 per cent reduction in PM_{2.5} emissions by 2020 in Europe are expected to lead to a 40 per cent fall in the associated years of life lost compared to the year 2000; nonetheless, PM_{2.5} air pollution is still expected to shorten statistical life expectancy by 4.6 months (Amann *et al.* 2011). However, if the new National Emission Ceilings in Europe are implemented the benefits will outweigh the costs 12–37 times depending on the valuation method (AEA 2010), and PM emissions could be reduced by 35–50 per cent depending on the portfolio of measures. Meanwhile, the US Environmental Protection Agency reports that lowered levels of ambient PM_{2.5} and ozone due to the US Clean Air Act are projected to result in avoided mortalities valued at US\$1.2 trillion in 2010 and US\$1.8 trillion in 2020 (2006 dollars). Reductions in exposure to particulate matter account for more than 90 per cent of these projected and realised benefits (USEPA 2010).



Using traditional cooking methods with biomass as a fuel causes severe indoor pollution by particulates and significant outdoor concentrations of black carbon and other particles. © Stillpictures/nbsp

Figure 2.12 National ambient air quality standards and WHO guidelines for PM₁₀

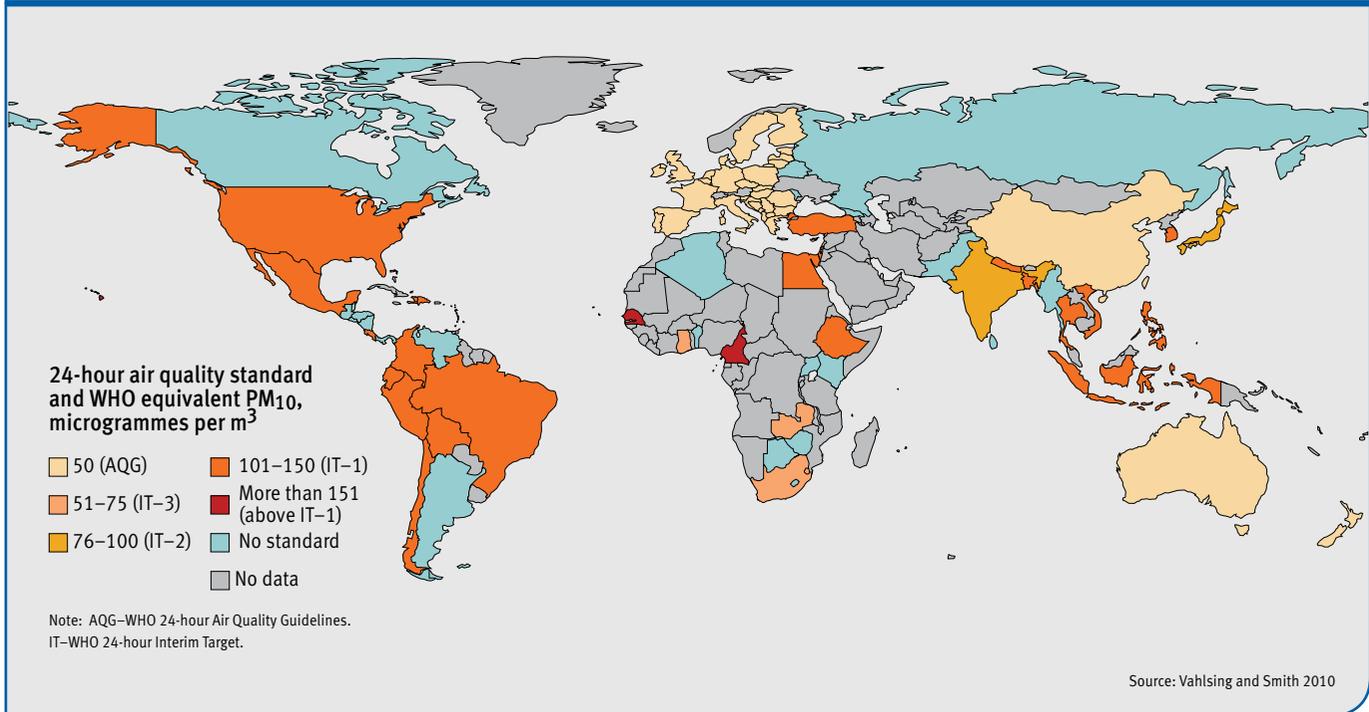
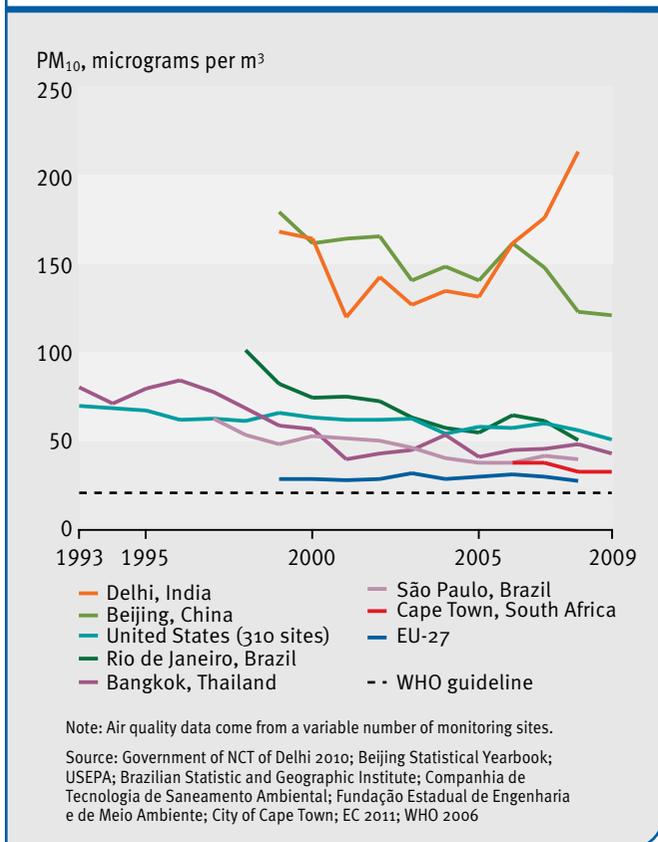


Figure 2.13 Urban PM₁₀ trends in selected regions and cities, 1993–2009



There are some uncertainties that need to be resolved to inform better policy making for particulate matter and health. These include the concentration and impact of particle sizes and a better understanding of the nature of primary and secondary PM pollution in different locations through monitoring, emission inventories and modelling, as well as through the use of source apportionment and estimation of the economic value of health impacts. Efforts to harmonize ambient air quality standards and the building of capacity have the potential to fast-track PM reduction in developing countries, amplifying the successful policies and technologies applied in Europe and North America and in some Asian and Latin American cities.

Tropospheric and surface ozone

Tropospheric ozone (O₃) in the lower atmosphere, from 0–10 up to 20 km above the Earth’s surface, is responsible for ozone’s impact on warming. Ground-level or surface ozone refers to concentrations at ground level that affect both human health and ecosystems. There is mixed progress in controlling tropospheric ozone: peak concentrations have decreased in Europe and North America, and North America, while background concentrations have increased. In rapidly industrializing regions both background and peak concentrations have been steadily rising (Royal Society 2008).

Ozone causes harm in three main ways. Firstly, surface ozone damages human health and its impact is considered second only to particulate matter. It is responsible for an estimated 0.7 million respiratory deaths globally each year (Anenberg *et al.* 2010), more than 75 per cent of which are in Asia. Ozone

Box 2.5 Tropospheric ozone

Related goals

Protect human health, crop yields, ecosystems and climate

Indicators

Precursor emissions; ozone levels

Global trends

Mixed progress in relation to CLRTAP targets: some reductions in EU and North America and mostly increasing concentrations in Asia; data for Africa is insufficient

can also have chronic health effects resulting in permanent lung damage (Royal Society 2008).

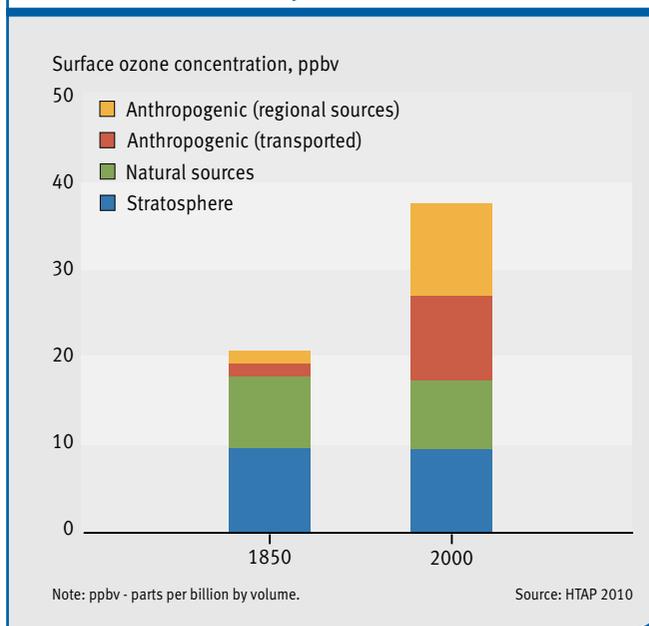
Secondly, surface ozone is the most important air pollutant causing damage to vegetation (Emberson *et al.* 2009; Ashmore 2005), diminishing crop yields and forest productivity and altering net primary productivity. Estimates suggest, for example, that ozone-induced yield losses range between 3 and 16 per cent for four staple crops – maize, wheat, soybean and rice – which translate into annual global economic losses of US\$14–26 billion (HTAP 2010).

Lastly, ozone is the third most important greenhouse gas after CO₂ and methane (IPCC 2007), but is classified as a short-lived climate forcer due to its residence time in the atmosphere of just days to weeks. Tropospheric ozone is estimated to have been responsible for a change in radiative forcing of +0.35 (-0.1, +0.3) watts per m² since pre-industrial times, compared to a combined anthropogenic radiative forcing of +1.6 (-1.0, +0.8) watts per m² (IPCC 2007). These ozone-induced changes are thought to be responsible for 5–16 per cent of the global temperature change since pre-industrial times (Forster *et al.* 2007). Reductions in biomass caused by ozone also influence the amount of carbon sequestered within terrestrial ecosystems. This effect is estimated to increase atmospheric CO₂ concentrations such that the additional radiative forcing could exceed warming due to the direct radiative effect of tropospheric ozone in the atmosphere (Sitch *et al.* 2007).

Ozone is not directly emitted into the atmosphere but rather is formed when precursor pollutants – nitrogen oxides and volatile organic compounds, including methane, and carbon monoxide – react in the presence of sunlight. As such, ozone concentrations tend to be higher at some distance – tens to thousands of kilometres – downwind of precursor pollutant sources, causing ozone to pollute at the local, regional and hemispheric scale.

Photochemical reactions account for approximately 90 per cent of the ozone in the troposphere, with the remaining 10 per cent directly transported from the stratosphere. Around 30 per cent of tropospheric ozone is due to anthropogenic emissions, with 40 per cent of the change in the global ozone burden since pre-

Figure 2.14 Sources of ozone over polluted regions of the northern hemisphere, 1850 and 2000



industrial times due to increases in methane, and the remainder to increases in emissions of nitrogen oxides, carbon monoxide and volatile organic compounds other than methane (HTAP 2010). The origin of ground-level or surface ozone relevant to effects on human health and ecosystems across the polluted regions of the northern hemisphere is 20–25 per cent from the stratosphere and a similar proportion from natural precursor sources including lightning and emissions from soils, vegetation and fire, along with oxidation of naturally occurring methane. The anthropogenic contribution thus typically exceeds 50 per cent over these regions (Figure 2.14).



Surface ozone does more damage to food crops than any other air pollutant. © Evgeny Kuklev/iStock



Ground-level ozone is one of the major contributors to city smog. © T. Kimura

Elevated ozone concentrations tend to be associated with regions experiencing high levels of uncontrolled emissions from industrial and urban centres as well as seasonal periods with high solar radiation. This causes high variability in global and seasonal concentrations. Regions in North America, Europe and Asia have been identified as having a high anthropogenic ozone load (Figure 2.15).

The targets defined for tropospheric ozone in the United Nations Economic Commission for Europe (UNECE) region are now being exceeded at many locations. Coordinated action in Europe, however, has resulted in emissions of nitrogen oxide and volatile organic compounds currently being 30 and 35 per cent lower

than in 1990, leading to reductions in short-term peak ozone concentrations to daily peak values of around 60 micrograms per m³ of air. In contrast, mean ozone concentrations at many locations have been increasing due to a variety of different factors. For example, local emission reductions of nitrogen oxides, and hence nitric oxide, remove a key mechanism of ozone destruction and can result in increases in concentrations in urban areas (Royal Society 2008). There is also evidence of background ozone concentrations increasing by up to 10 micrograms per m³ of air per decade since the 1970s (Royal Society 2008) due to changes in stratospheric ozone incursions, hemispheric transport and ozone formation responding to climate change. This will increase both mean and peak ozone levels.

Global photochemical modelling studies performed for the HTAP (2010) assessment provide estimates of changes in surface ozone concentration for those regions that currently show the highest concentrations. These data indicate recent reductions in surface ozone in North America and Europe, which are likely to be due to effective controls of nitrogen oxides and volatile organic compounds over the past two decades in response to the US Clean Air Act and CLRTAP and EU targets in Europe. In contrast, trends in Asia are continuing upwards due to continued rapid industrialization across the region (Figure 2.15). However, these regional trends may hide large local variations.

Future changes in tropospheric ozone concentrations have been explored using a number of different global photochemical models for a variety of emission scenarios and provide variable results (Figure 2.16). The HTAP (2010) assessment used a mean from six global models to assess the implications of emission changes between 2000 and 2050 following the RCP emission

Figure 2.15 Regional changes in concentrations of surface ozone, 1960–2000

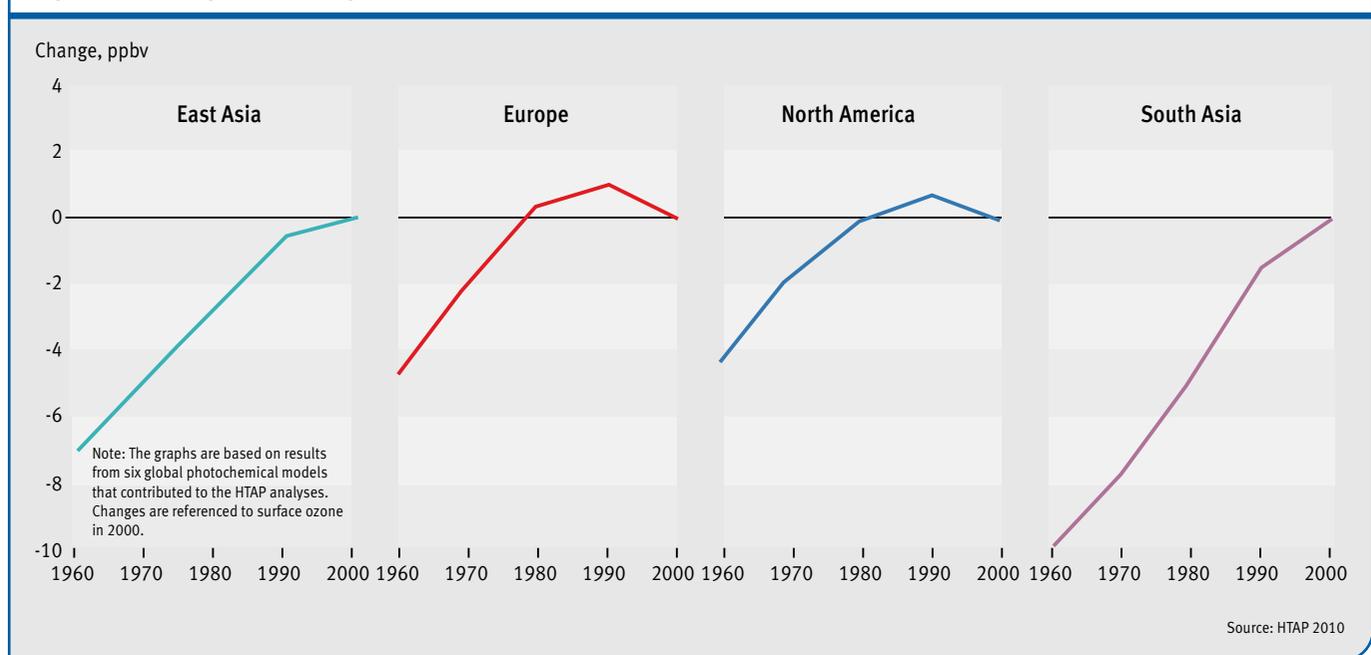
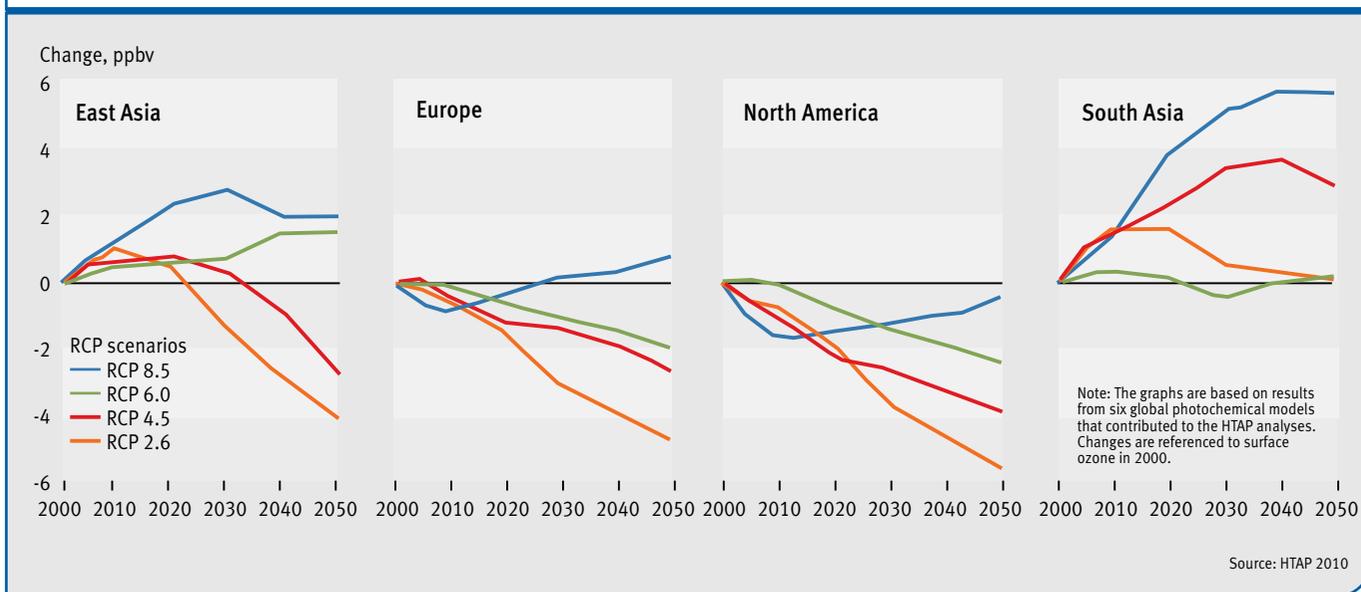


Figure 2.16 Projected changes in surface ozone concentrations over polluted regions of the northern hemisphere, 2000–2050



scenarios. The outlook for ozone concentrations is heavily dependent on global and regional emission pathways.

Assessment of the effectiveness of policies introduced to control ozone requires an extended global monitoring network covering rural as well as urban locations. Improved understanding of ozone's impact on human health and ecosystems and how climate change will affect its formation, as well as how ozone acts in combination with other stressors such as global warming and excessive nitrogen deposition, will also be important. The growing interest in ozone as a short-lived climate forcer and the associated human health, arable-agriculture and ecosystem benefits that its reduction might bring (UNEP/WMO 2011) make this a pollutant of particular interest for policy intervention.

Progress on internationally agreed goals

There are two examples of substantial progress in solving issues and achieving targets: protection of the stratospheric ozone layer and the removal of lead from petrol.

Stratospheric ozone layer

Global regimes to address stratospheric ozone depletion include the 1985 Vienna Convention for the Protection of the Ozone Layer and its 1987 Montreal Protocol on Substances that Deplete the Ozone Layer. The latest scientific assessments confirm the success of the action taken under the Montreal Protocol to eliminate consumption of ozone-depleting substances (Figure 2.17) (WMO 2011; UNEP 2010).

Stratospheric ozone protects humans and other organisms because it absorbs ultraviolet-B (UV-B) radiation from the sun. In humans, heightened exposure to UV-B radiation increases the risk of skin cancer, cataracts and suppression of the

Box 2.6 Stratospheric ozone

Related goals

Protection of the stratospheric ozone layer

Indicators

Consumption of ozone-depleting substances; atmospheric burden; annual extent of the Antarctic ozone hole

Global trends

Significant progress

immune system. Excessive UV-B exposure can also damage terrestrial plant life, single-cell organisms and aquatic ecosystems. In the mid-1970s, it was discovered that the thinning of the stratospheric ozone layer was linked to the steady increase of chlorofluorocarbons (CFCs) – used for refrigeration and air conditioning, foam blowing and industrial cleaning – in the atmosphere.

The most severe and surprising ozone loss – which came to be known as the ozone hole – was discovered to be recurring in springtime over the Antarctic. Thinning of the ozone layer has also been observed over other regions, such as the Arctic (Manney *et al.* 2011) and northern and southern mid-latitudes.

Despite the drastic reduction in consumption of ozone-depleting substances (Figure 2.17), their concentrations in the stratosphere remain high (as shown by the Ozone Depleting Gas Index (ODGI), Figure 2.18) as they have long atmospheric lifetimes. Figure 2.18

Figure 2.17 Consumption of ozone-depleting substances, 1986–2009

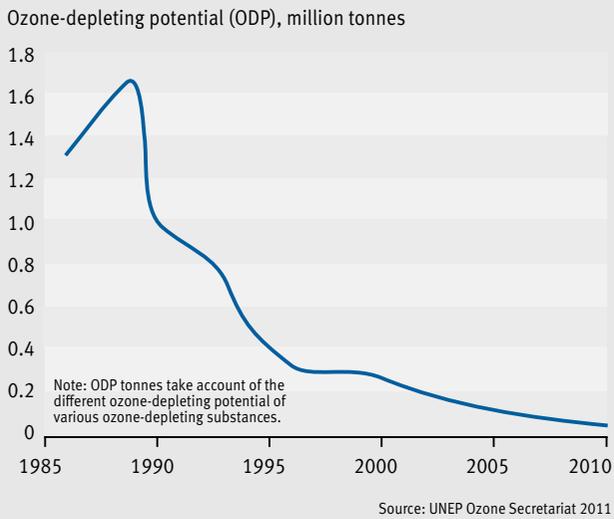
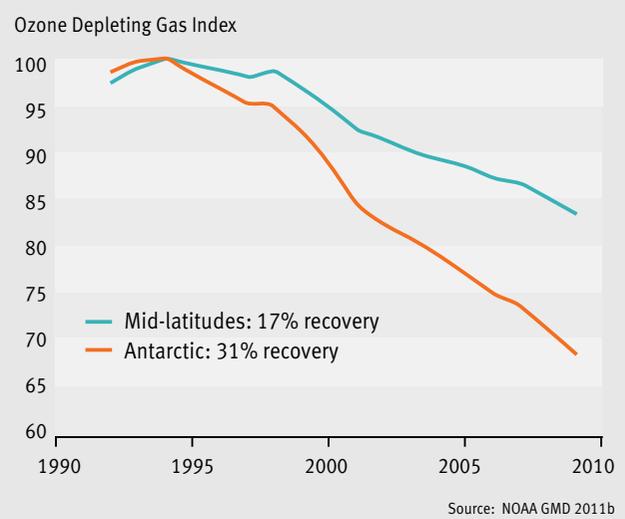


Figure 2.18 Reduction of ozone-depleting substances in the stratosphere, 1994–2009



shows a 31 per cent recovery from a peak in 1994 at mid-latitudes and a 17 per cent recovery in the Antarctic.

The hole in the Antarctic ozone layer is the clearest manifestation of the effect of ozone-depleting substances: springtime Antarctic total column ozone losses continue to occur each year, with the extent affected by meteorological conditions. Figure 2.19 shows

the development of Antarctic ozone depletion over the last three decades, measured from 19 July to 1 December each year. The largest ozone hole on record occurred in 2006 (WMO 2011).

Model simulations for an ozone depletion scenario without the Montreal Protocol, the “World Avoided” scenario, show that there would have been a 300 per cent increase in the UV radiation at

Figure 2.19 Antarctic ozone hole extent, 1980–2010

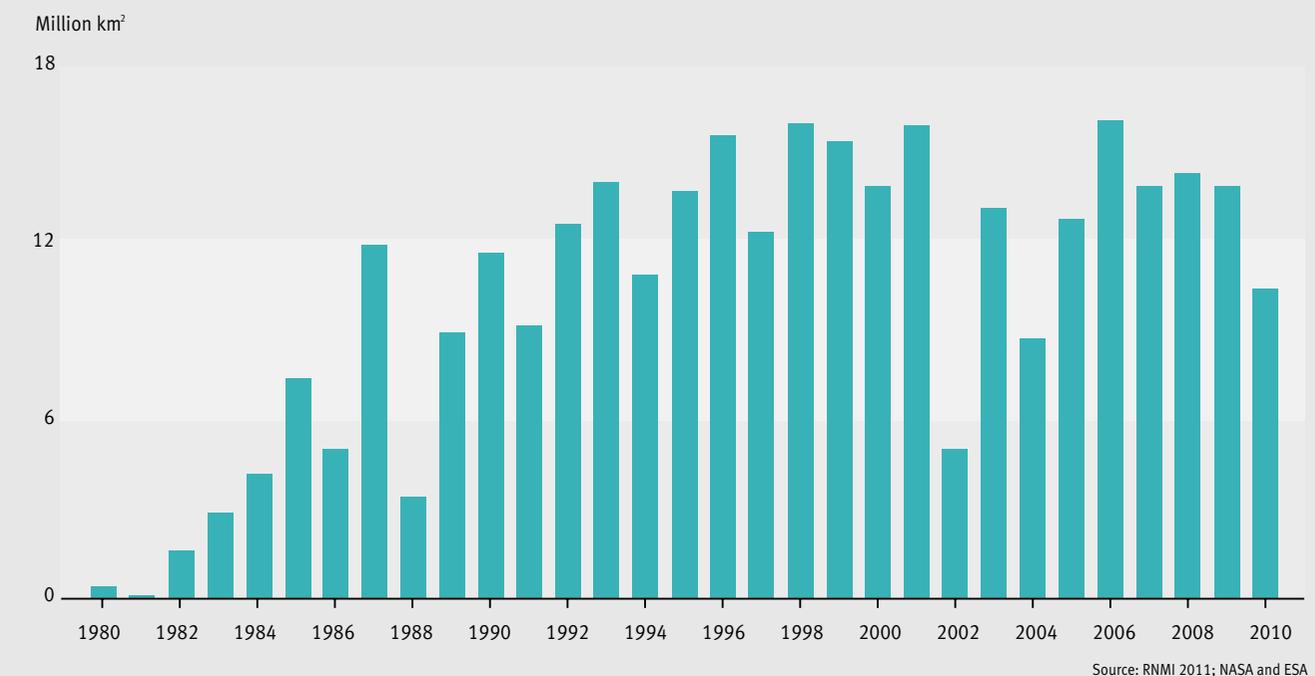
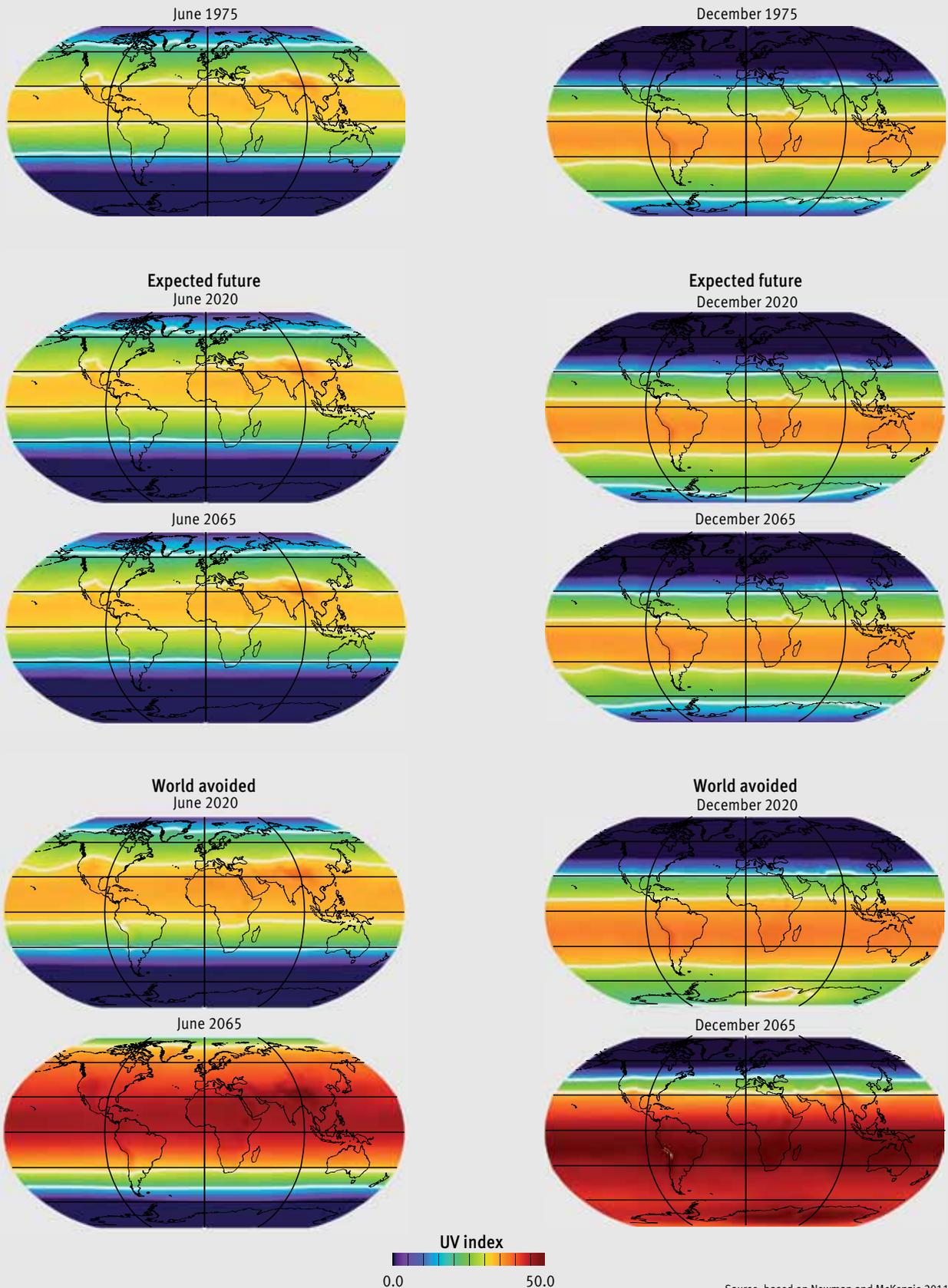


Figure 2.20 The World Avoided modelled UV index, 1975, 2020 and 2065





The side of an old gasoline pump with a sign cautioning that it contains lead. © Tim Messick

mid-northern latitudes or a 550 per cent increase in UV radiation at the mid-latitudes by 2065 compared to 1980 levels (Figure 2.20) (Newman and McKenzie 2011). Such a drastic increase in UV-radiation would have had serious consequences for both human health and the environment. In the United States alone, it is estimated that 22 million cases of cataract will be avoided for people born between 1985 and 2100 and 6.3 million skin cancer deaths will be avoided up to the year 2165 as a result of the Montreal Protocol (USEPA 2010).

The most recent amendment of the Montreal Protocol, in 2007, accelerated the phase-out of hydrochlorofluorocarbons (HCFCs), contributing to a reduction in global warming potential (GWP) of about 18 billion tonnes of CO₂-equivalent emissions.

The current phase-out of ozone-depleting substances is expected to lead to recovery of the ozone layer at different times in different regions (WMO 2011). For the world as a whole, annually averaged total column ozone is projected to return to 1980 levels between 2025 and 2040, but this will take until mid-century in the Antarctic, with small episodic Antarctic ozone holes likely to persist even at the end of the 21st century (WMO 2011). Annually averaged total column ozone is projected to return to 1980 values between 2015 and 2030 over northern mid-latitudes, while for southern mid-latitudes it is projected to recover between 2030 and 2040.

Box 2.7 Lead in petrol

Related goals

Prevention of exposure to lead

Indicators

Number of countries with leaded petrol

Global trends

Globally phased out except in six countries

Despite the successful implementation of certain Montreal Protocol provisions, some issues remain regarding the capture of ozone-depleting substances in old equipment and the destruction of collected or stockpiled appliances.

Removal of lead from petrol

The goals in the Johannesburg Plan of Implementation to reduce exposure to lead have largely been met, with most countries having phased out lead in petrol since 2002, although there is evidence that leaded petrol is still sold in at least six countries (Figure 2.21).

Lead poisoning, at all levels of exposure, causes adverse and often irreversible health effects in humans, particularly children, and accounts for about 9 million DALYs or around 0.6 per cent of the global burden of disease (WHO 2009). Acute exposure to high levels of lead affects the brain and central nervous system, causing coma, convulsions and even death. Lead can also adversely affect the immune, reproductive and cardiovascular systems, even at relatively low levels (WHO 2010). There is no threshold of exposure under which adverse effects cannot be detected (Lanphear *et al.* 2005; Schneider *et al.* 2003; Lovei 1998; Schwartz 1994).

While exposure to lead and lead poisoning may be due to many different sources and products – including paints and pigments, electronic waste, cosmetics and toys, traditional medicines, contaminated food and drinking water systems – lead in petrol has been the biggest contributor to global environmental lead contamination (WHO 2010).

A health-based regulation to remove lead from petrol in the United States was made in 1973 after the US Environmental Protection Agency concluded that lead emissions caused serious damage to the nervous system and serious impacts on the health of children in particular (Bridbord and Hanson 2009). Similar conclusions in Japan led to it becoming the first country to market unleaded petrol and, by 1981, less than 3 per cent of petrol sold there was leaded (Wilson and Horrocks 2008).

From the period 1976–1980 to the period 1999–2002, the United States saw a 98 per cent reduction in the proportion of children aged one to five with levels of more than 10 micrograms of lead per decilitre of blood (CDC 2005). Other studies worldwide showed a strong correlation between decreased use of lead in petrol and reductions of lead in blood (Figures 2.22 and 2.23) (Thomas *et al.* 1999).

Interventions to prevent lead poisoning have demonstrated very large economic benefits. An analysis of the direct medical and indirect societal costs associated with lead poisoning in children in the United States found these to be US\$43 billion annually, even at the relatively low levels of exposure to lead at the time (Landrigan *et al.* 2002). Another economic assessment, in this case for the full lifetime productivity of people, estimated that the increases in child intelligence, and thus their in-lifetime economic productivity, resulting from the removal of lead from petrol

produced a benefit of between US\$110 billion and US\$319 billion in each birth cohort in the United States (Grosse *et al.* 2002).

According to Gould (2009), for every US\$1 spent to reduce lead hazards, there would be a benefit of US\$17–220, a better cost-benefit ratio than that for vaccines, which have long been described as the single most cost-beneficial medical or public health intervention. Another methodology that uses GDP extrapolation applied to published literature showed the global

benefits of the phase-out of lead in petrol to be US\$1–6 trillion per year, with a best estimate of US\$2.45 trillion per year, roughly 4 per cent of global GDP (Tsai and Hatfield 2011).

Recent evidence on health impacts has led the US Environmental Protection Agency to tighten its rolling three-month average air quality standard for lead from 1.5 micrograms of lead per m³ of air in 1978 to 0.15 micrograms per m³ in 2008 (USEPA 2008). The WHO annual ambient air guideline for lead remains at

Figure 2.21 Leaded petrol phase-out, 2002 and 2011

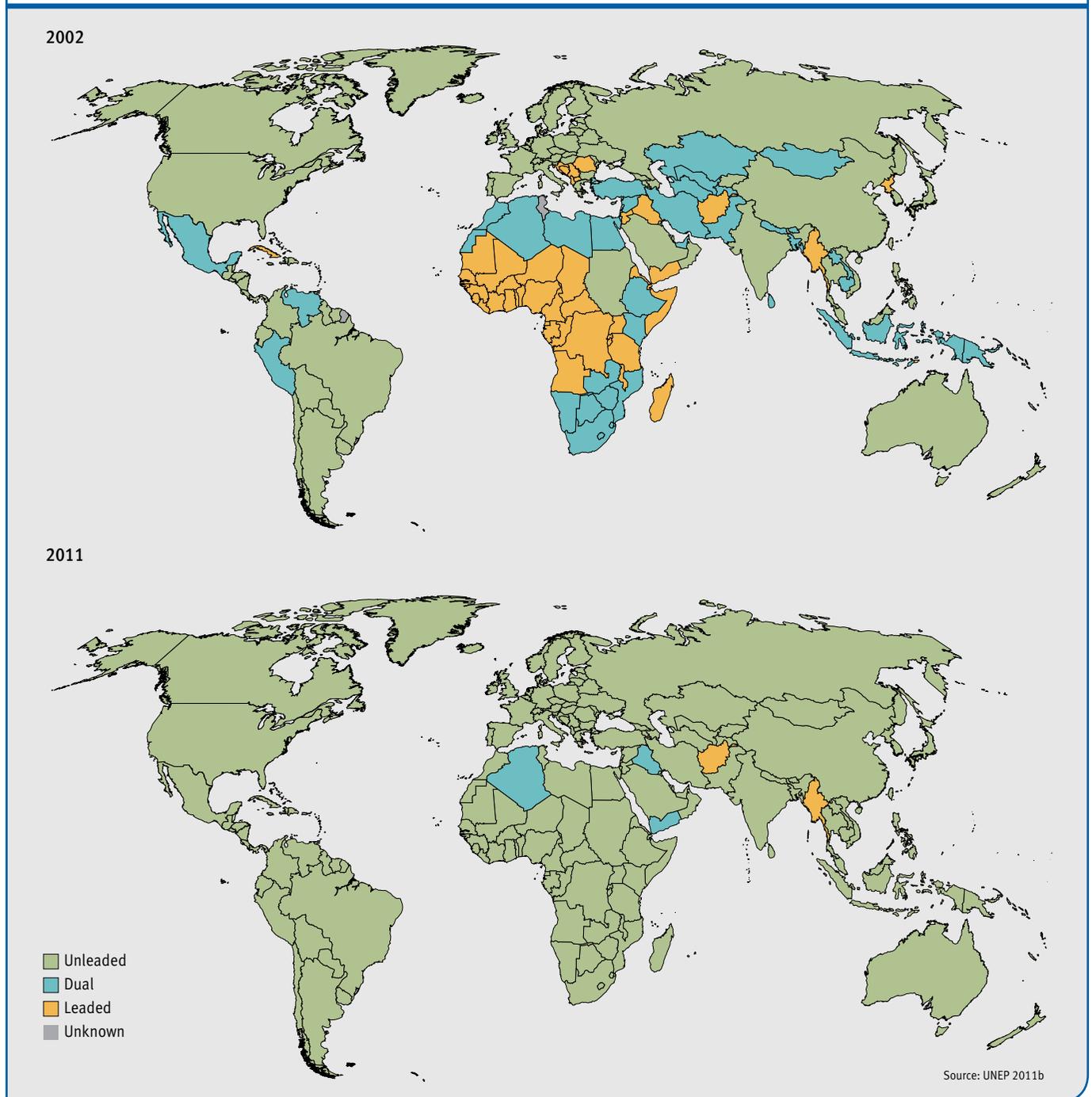


Figure 2.22 Petrol and blood lead levels in Sweden following the phase-out of lead in petrol, 1976–2004

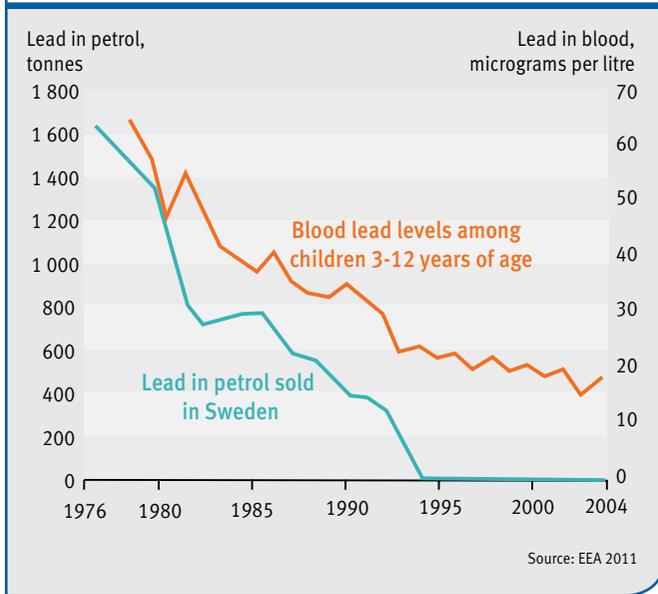
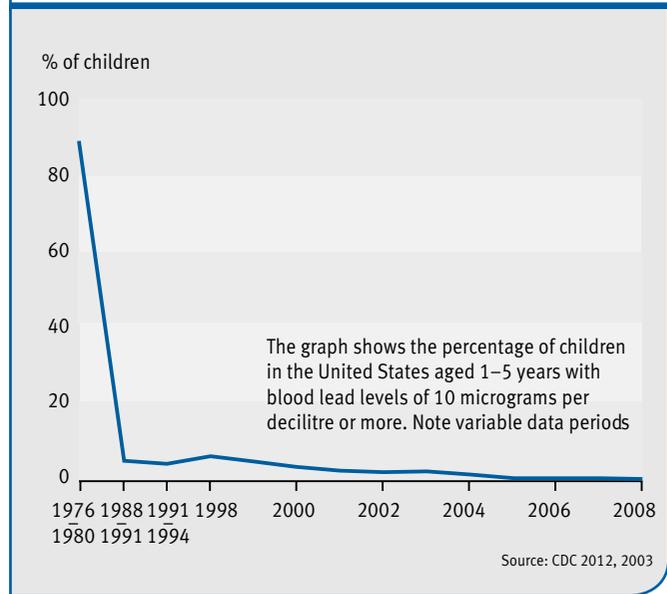


Figure 2.23 Blood lead levels in the United States following the phase-out of lead in petrol, 1976–2008



0.5 micrograms of lead per m³ of air (WHO 2000). The removal of lead from petrol and the consequent reductions in health risks is an outstanding global success story, with the complete global elimination of lead in petrol expected within a few years.

EMERGING ISSUES

The most important new issue in the study of the atmospheric environment is the role of short-lived climate forcers, especially methane, tropospheric ozone and black carbon (UNEP/WMO

2011). A subset of hydrofluorocarbons (HFCs) are also important short-lived climate forcers (UNEP 2011c).

Black carbon particles in the atmosphere have a significant impact not only on human health but also on climate. They darken snow and ice surfaces, lower their albedo and increase their absorption of sunlight, which, along with atmospheric heating, exacerbates the melting of snow and ice around the world, including in the Arctic, the Himalayas and other glaciated and snow-covered



Snow and ice cover in the Himalayas is affected by aerosols, including black carbon. © Arsgera



The production of bricks in traditional kilns is a locally significant source of black carbon in South Asia. © Alexander Kataytsev/iStock

regions. This affects the water cycle and may increase risks of flooding. Methane is a powerful greenhouse gas and an important precursor for ozone generation. Methane, black carbon and tropospheric ozone are fundamentally different from the longer-lived greenhouse gases as they remain in the atmosphere for a relatively short time. Reducing black carbon and methane emissions now will slow the rate of climate change within the first half of this century (Shindell *et al.* 2012; UNEP/WMO 2011).

A second major emerging issue is the health effect of fine particles of natural origin. Every year, very large amounts of soil-derived dust and particles from wildfires engulf major populated areas. These can include soil particles from arid regions being deposited on coastal cities of China, Saharan dust reaching cities in Africa and the Mediterranean, and dust from drought-affected inland areas being deposited on cities in the United States and Australia. In addition, smoke from wildfires commonly raises particulate concentrations in Africa, Siberia, the Mediterranean, the United States, South East Asia and Australia. These particles can have major impacts on human health and a recent study suggests that almost 300 000 excess deaths per year can be attributed to fine particles of natural origin (Liu *et al.* 2009a, 2009b). The sources can, however, be at least partially controlled (Chapter 3). Major interventions to re-vegetate degraded landscapes are continuing in several countries and the 2003 ASEAN Agreement on Transboundary Haze Pollution is an example of an international agreement aimed at addressing the international transport of particles generated from forest burning.

As understanding of the relationship between particle size, the number of particles and health impacts has improved, concern has grown about the impacts of fine particles (smaller than 2.5 micrometres in diameter) and ultrafine particles (1 micrometre and sub-micrometre sizes) on respiratory and cardiovascular health (Schmid *et al.* 2009; Valavanidis *et al.* 2008). As the volume of evidence is rapidly growing, it is likely that in the next few years air quality standards and guidelines to protect health by controlling exposure to ultrafine particles will be developed and become a focus of air quality policy, monitoring and management.

A number of new approaches to address the challenges of climate change have been proposed, including carbon capture and storage and geo-engineering (IPCC 2005; Rasch *et al.* 2008).

ATMOSPHERIC GOVERNANCE AND AN INTEGRATED APPROACH TO MANAGEMENT

In this section a simple analytical framework based on the level of concern for the different issues, the relative cost of addressing the problems, and the complexity of managing atmospheric issues is used to evaluate the governance of atmospheric problems. It suggests there is no one-size-fits-all solution to most atmospheric problems (Levy *et al.* 1993). The use of targets and timetables that worked for stratospheric ozone depletion may stall negotiations over climate change (Sunstein 2007). Emissions trading schemes that worked well for the reduction of sulphur dioxide in some developed countries may need to be complemented by other measures in developing countries (Chang and Wang 2010). Many emission sources release both greenhouse gases and air pollutants; some air pollutants have an additional effect on the climate; and reducing consumption of ozone depleting substances also reduces their impact on climate. There will be a growing need for decision-making frameworks and enabling environments that explicitly recognize the integrated nature of the atmosphere.

The elimination of lead from petrol was made easier by a cost-effective alternative that proved easy to communicate to politicians and other stakeholders. With the well-timed support of international initiatives such as the UNEP Partnership for Clean Fuels and Vehicles, one country after another introduced lead-free fuels (Hilton 2006).

Though there was no global binding agreement on the phase-out of lead in petrol, there are parallels with the phase-out of ozone-depleting substances as a relatively manageable problem with cost-effective solutions and a high level of concern. For the elimination of substances that harm the ozone layer, governments agreed to the Vienna Convention, setting in motion an international negotiation process that culminated in the Montreal Protocol. The protocol became the model for other international agreements that called for a series of targets and timetables to eliminate ozone-depleting substances in the developed world, and for the creation of a multilateral fund to finance replacement technologies for developing countries beginning to manufacture CFCs (Benedick 1998). The process of arriving at this agreement helped raise concern, lower costs and clarify complexities.

Progress with other pollutants has been more uneven. For example, in the case of sulphur dioxide, existing technology, affordable abatement costs and growing understanding have made the issue increasingly manageable in much of the developed world. However, while target setting and the installation of flue-gas desulphurization have become common, growth in the number of coal-fired power plants has overwhelmed efforts to reduce emissions. Consequently, levels of acid deposition in East Asia remain high.

The health impacts of particulate matter make its control the highest priority. However, measures can be costly and complex due to a multiplicity of industrial, transport, energy, commercial, domestic and natural sources, especially in developing countries. Various measures, such as technological improvements



A compact electric car, intended for urban use, charges its battery in a special charging station. © iStock/code6d

in vehicles, increased engine efficiency, cleaner fuels and particulate filters, have been successfully applied in different cities. Across the developed world urban levels of particulate matter began to fall sharply in the 1950s and 1960s. Cleaner technologies have enjoyed some success in reducing emissions in developing countries, but have not been sustained in rapidly growing cities where high demands for motorization, energy and industrial products have increased aggregate emissions. Both the complexity of the issue and the costs have hampered progress. To reduce exposure to indoor particulate matter national policies, including on rural development and energy, need to be mainstreamed into overall development policy.

Governance issues related to climate change have a high level of complexity, mixed levels of concern and long lead times between actions and benefits, often beyond political timescales. The governance approach for climate change has in many ways followed a similar approach to that of the ozone layer, but with different results due to differences in the nature of the issues. A growing degree of concern led to a global agreement, the UNFCCC, which allowed negotiation of the Kyoto Protocol. This was intended to initiate the process of reducing anthropogenic greenhouse gas emissions, but even if fully implemented was never designed to be enough to stay within the UNFCCC agreed limit of a 2°C temperature increase.

The approach of developing binding national targets within a global framework has so far not delivered emission reductions that would help achieve climate targets and internationally agreed goals. In the medium term, a promising approach appears to be the development of nationally appropriate mitigation actions – or NAMAs – to encourage countries to contribute to actions in a national context.

The achievement of global climate goals will most likely require a transformational change addressing the main drivers

of emissions (Chapter 16) such as in the way electricity is generated, the efficiency with which energy and resources are used, and the management of terrestrial ecosystems (Chapters 3 and Chapter 12). Consumption levels and production processes may require the introduction of approaches such as a circular economy in which material flows are either made up of biological nutrients designed to re-enter the biosphere, or materials designed to circulate without entering the biosphere (Braungart *et al.* 2007). Such changes take time and, in the short term, existing cost-effective options need to be rolled out as far and as rapidly as possible to deliver early emission reductions that put the world on a path towards achieving established climate goals.

Mitigating near-term climate change – the warming likely to be experienced over the next two to four decades – is important to prevent damage to vulnerable ecosystems such as the Arctic, and to vulnerable societies such as those in drought- or flood-prone regions. Addressing CO₂ is not likely to be sufficient to mitigate warming in these timescales, partly because it is long-lived. Fortunately, near-term warming can be addressed by additional complementary policy action that reduces concentrations of short-lived climate forcers, including black carbon, methane and tropospheric ozone (Box 2.8) (Shindell *et al.* 2012; UNEP/WMO 2011). Addressing these short-lived substances is an example of an integrated approach to atmospheric governance that provides an opportunity for policy development to meet multiple goals in a cost-effective way. The improved awareness of atmospheric brown clouds emphasizes the integration of different atmospheric issues (Box 2.9). There is increasing evidence that the Antarctic ozone hole has affected the surface climate in the southern hemisphere (Polvani *et al.* 2011), and further links also exist between climate change and ozone-depleting substances as many are also very strong greenhouse gases. Indeed, avoiding emissions of CFCs has brought about a significant contribution to climate change mitigation (Velders *et al.* 2007).

These interactions and links between different atmospheric issues provide opportunities to improve progress in reaching internationally set goals, maximizing benefits and avoiding policy conflicts. To make rapid progress, scientific knowledge needs to be properly presented to policy makers to allow them to deal more effectively with the complexity of the issues. The way in which options are analysed, costs and benefits weighed up, and evidence-based policies developed, requires considerable improvement. This will require closer interaction between the science and policy communities, increased stakeholder participation, capacity enhancement and technology transfer.

CONCLUSIONS, GAPS AND OUTLOOK

Concern for the impacts of atmospheric issues at global, regional and national scales has led to considerable efforts to control emissions to meet internationally agreed goals and targets. Some issues have been effectively dealt with. For others there has only been partial success, with improvements in some regions but problems remaining in others.

Targets to protect the global atmosphere from air pollution are being met for stratospheric ozone depletion and lead in petrol.

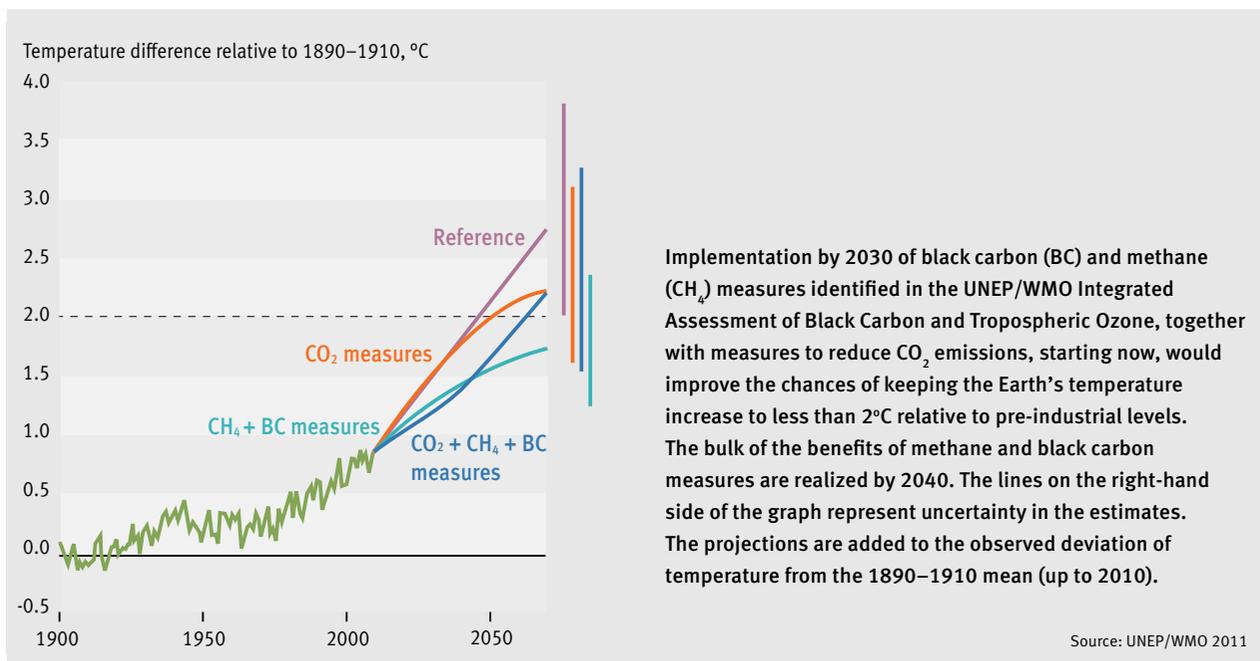
Box 2.8 Complementary actions to limit near-term climate change and improve air quality

Implementing a limited number of measures targeting black carbon, tropospheric ozone and methane has the potential to reduce the rise in global temperature projected for 2050 by 0.5°C – roughly half of the warming in the reference scenario (Figure 2.24) – substantially reducing the rate at which the world warms over the next few decades (Shindell *et al.* 2012; UNEP/WMO 2011). About half of this reduction could be attributed to reductions in methane emissions and about half to measures addressing incomplete combustion and targeting black carbon emissions. The projected reduced warming in the Arctic, about 0.7°C lower than the reference scenario in 2050 according to this research, would be likely to be greater than that seen globally (UNEP/WMO 2011). There are further benefits for regional climate as several detailed studies of the Asian monsoon suggest that regional forcing by absorbing particles substantially alters precipitation patterns

(UNEP/WMO 2011). As the reductions in atmospheric forcing are largest over the Indian sub-continent and other parts of Asia, the emission reductions might have a substantial effect on the Asian monsoon, mitigating disruption of rainfall patterns.

Full implementation of the identified measures would also substantially improve air quality, reducing premature deaths globally due to significant reductions in indoor and outdoor air pollution, and improving crop yields. The reductions in PM_{2.5} and tropospheric ozone concentrations resulting from the implementation of the measures could, by 2030, avoid 2.4 million premature deaths (within a range of 0.7–4.6 million deaths) and the loss of 52 million tonnes of the global production of maize, rice, soybean and wheat each year (within a range of 30–140 million tonnes), or 1–4 per cent (UNEP/WMO 2011).

Figure 2.24 Projected effects of measures to reduce CO₂, methane and black carbon emissions in relation to a reference scenario



For the majority of the world, however, most air quality guidelines are not being met as there is insufficient implementation of policies. Meanwhile, important ecosystems are experiencing pollution loads in excess of critical thresholds. In the near term, atmospheric issues such as particulate matter and other pollutants could, with adequate commitment and resources, be effectively addressed by the wider implementation of existing policies and technologies.

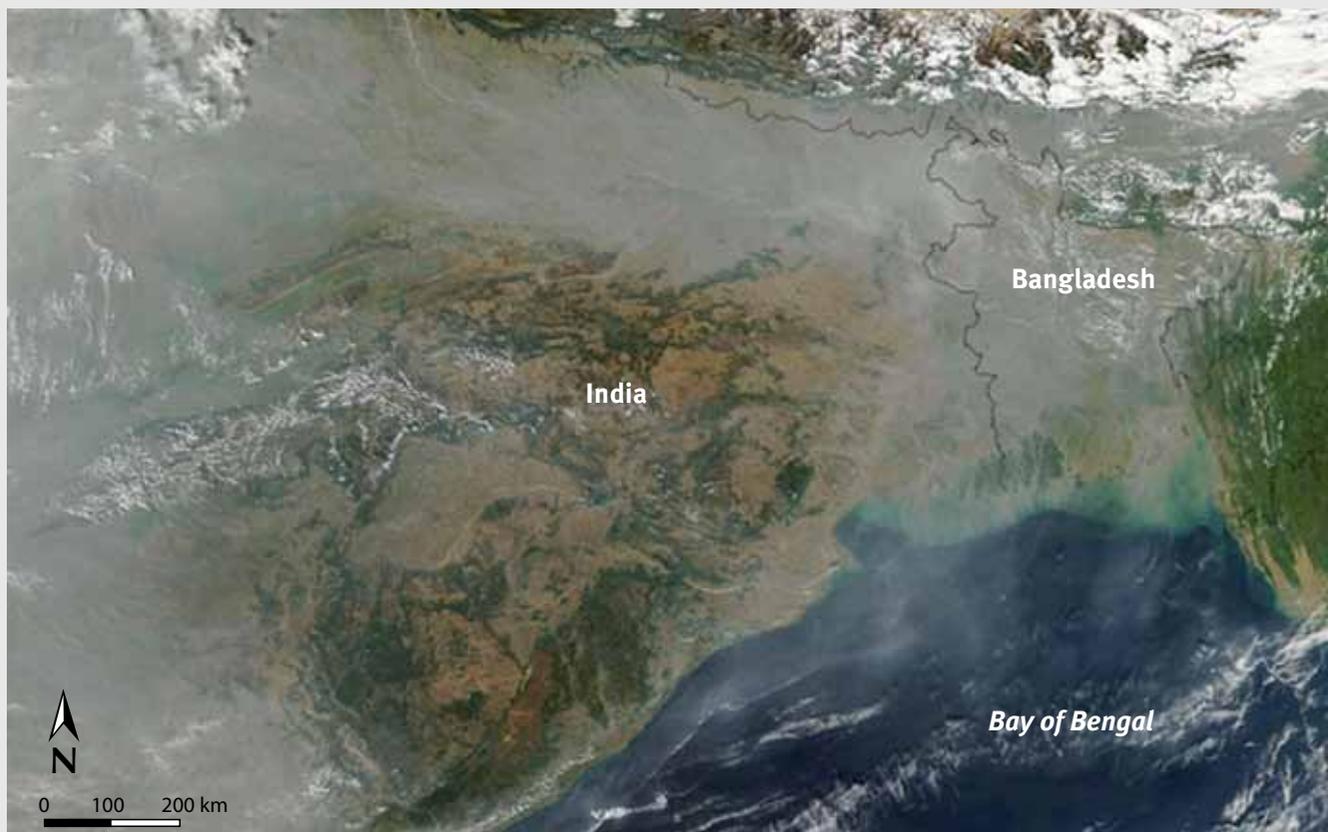
The current development trajectory, based on existing models of international governance, is unlikely to meet internationally agreed atmospheric goals, especially those for mitigating climate change and reducing the health impacts of pollutants. Carefully selected approaches at national and regional scales need to be encouraged and facilitated by global coordination to increase the chance of reaching the targets in the near term.

Box 2.9 Atmospheric brown clouds

Atmospheric brown clouds, which have been observed as widespread layers of brownish haze, particularly in South Asia (Figure 2.25), are regional-scale plumes of air pollutants consisting mainly of aerosol particles such as black carbon and precursor gases that produce aerosols and ozone. These clouds significantly affect the regional climate, the hydrological cycle and glacial melting. The pollutants can be transported by long-range and regional transport

phenomena that push this haze towards the Himalayan ridge, where plain-to-mountain wind systems favour air-mass transport to high altitudes (Bonasoni *et al.* 2010). The widespread nature of atmospheric brown clouds and findings related to their diverse and adverse effects have increased the need for the development of science, capacity and emission-reduction measures within an integrated framework.

Figure 2.25 Atmospheric brown cloud over part of South Asia



Source: NASA-MODIS

Climate change presents the global community with one of the most serious challenges to achieving development goals. Serious impacts from climate change are unlikely to be avoided on the basis of current emission reduction pledges. In the medium term, progress could be made by encouraging further national pledges, taking into account individual country circumstances, and by the wide application of current technological and policy approaches.

Measures to reduce emissions of short-lived climate forcers could contribute to reducing the temperature increase in the near term but, ultimately, a transformation in the way energy is provided and the efficiency with which electricity and other resources

are used, coupled with a shift in consumption and production patterns and investment in innovation, will be required to achieve long-term climate goals. Such transformative change will also affect other atmospheric problems. But action should start now with the measures that are currently available while transformation takes place. Such action would bring significant benefits, particularly if the atmospheric issues and required policies were considered in an integrated way.

Table 2.5 provides a summary of progress and a prognosis for the development of key atmospheric issues in their relation to goals and targets.

Table 2.5 Progress towards goals (see Table 2.2)

A: Significant progress B: Some progress		C: Very little to no progress D: Deteriorating		X: Too soon to assess progress ?: Insufficient data	
Key issues and goals	State and trends		Outlook	Gaps	
1. Stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system					
Climate change limit the increase in global average temperature to less than 2°C above pre-industrial levels	C	Rising CO ₂ and other greenhouse gas emissions, and increasing concentrations; SLCF concentrations remain high and some are increasing Temperature increases observed globally and regionally over last decades	Efficiency improvements and some progress towards meeting Kyoto targets Likely to breach the 2°C limit without further commitment and action	Improvement in monitoring and reporting of pledged actions; financial and technical support to developing countries; policy integration of climate change and other atmospheric issues	
2. Protect the ozone layer by taking precautionary measures to control total global production and consumption of ozone-depleting substances (ODS) equitably, with the ultimate objective of eliminating them					
Stratospheric ozone depletion Zero consumption of ozone-depleting substances	A	About 98% achievement (in 2009) in reducing the production and consumption of substances covered by the Montreal Protocol Decreasing atmospheric concentrations Stabilization of the Antarctic ozone hole	Continued decrease in atmospheric concentrations of ozone-depleting substances; recovery of ozone layer by mid-century	Recovery and destruction of ozone-depleting substances; from equipment, chemical stockpiles, foams, and other products not yet released into the atmosphere	
3. Reduce respiratory diseases and other health impacts resulting from air pollution, with particular focus on women and children					
Particulate matter (urban/ outdoor) WHO guidelines and national targets	B	Outdoor concentrations of particulate matter in most parts of Europe and North America are within or are approaching WHO and EU guidelines; concentrations in Africa and Asia remain high	Slow progress in developing countries in Africa and Asia, as any efficiencies are likely to be offset by increased consumption and levels of activity	Monitoring, mainly in developing countries; standards for particulate matter, political will and awareness of the issues in some developing countries	
Particulate matter (indoor) Households cooking using biomass	C	In poor rural areas of the world, for example in parts of Africa and Asia, there is little access to cleaner cookstoves and fuels, and indoor particulate matter is very high; significant health impacts, especially for women and children	Continued poverty and other barriers will prevent the transition to modern fuels or use of improved cooking facilities	Monitoring and associated technology in developing countries; mechanisms to enable purchase of efficient cooking stoves, institutional strengthening, and political will to address the issue	
Tropospheric ozone WHO guidelines for health	B	Peak tropospheric ozone concentrations decreasing in Europe and North America except in ozone hotspots	Further reductions in Europe and North America will lead to decreased ozone, but there will be increases in precursors and ozone elsewhere	More ozone and precursor monitoring in developing countries; awareness of the issue	
4. Enhanced cooperation at international, regional and national levels to reduce air pollution, including transboundary air pollution and acid deposition					
Tropospheric ozone CLRTAP goals	B	Peak concentrations of ozone are decreasing due to diminishing precursor emissions (nitrogen oxides, volatile organic compounds, methane and carbon monoxide) in Europe and North America except in ozone hotspots; increasing concentrations elsewhere; background concentrations increasing	Improvements in some regions are being offset by an increase in background ozone	Technology to minimize emissions of ozone precursors; monitoring in rural settings; implementation of policies in different sectors for different precursor emissions; regional and inter-regional cooperation	
Sulphur dioxide WHO guidelines CLRTAP emission targets	B	Sulphur dioxide emissions and concentrations have been significantly reduced in Europe and North America	Overall sulphur dioxide emissions will decrease due to global desulphurization but increasing emissions are expected in some rapidly developing countries in Asia	Further sulphur dioxide emission reductions, especially in Asia	
Nitrogen WHO guidelines CLRTAP emission targets	B	Nitrogen dioxide concentrations globally remained constant due to reductions in North America and Europe off-setting slight increases in Africa, Asia and Latin America	In Africa, Asia and Latin America where nitrogen emissions are not high priority, increases in both nitrogen oxide and ammonia emissions are expected, especially from agriculture and motorization	Awareness of issues and policy focus; improved technology to minimize emissions of nitrogen; understanding of long-range transport and impacts in all regions	
5. Prevention of children's exposure to lead					
Lead Eliminate lead in petrol	A	Lead phased out in petrol globally except in six countries; lead blood levels in children have gone down	Lead from other sources, such as paint, has to be tackled globally	Policies and studies on lead in paint from developing countries	

REFERENCES

- AEA (2010). *Cost Benefit Analysis for the Revision of the National Emission Ceilings Directive*. http://ec.europa.eu/environment/air/pollutants/pdf/necd_cba.pdf
- Aldy, J.E., Krupnick, A.J., Newell, R.G., Parry, I.W.H. and Pizer, W.A. (2010). Designing Climate Mitigation Policy. *Journal of Economic Literature* 48(4), 903–934
- Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., Sandler, R., Schöpp, W., Wagner, F. and Winiwarter, W. (2011). Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications. *Environmental Modelling and Software* (in press). doi:10.1016/j.envsoft.2011.07.012
- Anenberg, S.C., Horowitz, L.W., Tong, D.Q. and West, J.J. (2010). An estimate of the global burden of anthropogenic ozone and fine particulate matter on premature human mortality using atmospheric modeling. *Environmental Health Perspectives* 118(9), 1189–1195
- ASEAN (2002). *ASEAN Agreement on Transboundary Haze Pollution*. http://www.aseansec.org/pdf/agr_haze.pdf
- Ashmore, M.R. (2005). Assessing the future global impact of ozone on vegetation. *Plant, Cell and Environment* 28, 949–964
- Barriopedro, D., Fischer, E.M., Luterbacher, J., Trigo, R.M. and García-Herrera, R. (2011). The hot summer of 2010: redrawing the temperature record map of Europe. *Science* 332(6026), 220–4
- Benedick, R.E. (1998). *Ozone Diplomacy: New Directions in Safeguarding the Planet*. Harvard University Press, Cambridge, MA
- Bleeker, A., Hicks, W.K., Dentener, F., Galloway, J. and Erisman, J.W. (2011). Nitrogen deposition as a threat to the world's protected areas under the Convention on Biological Diversity. *Environmental Pollution* 159, 2280–2288
- Bobbink, R., Hornung, M. and Roelofs, J.G.M. (1998). The effects of air-borne nitrogen pollutants on species diversity in natural and semi-natural European vegetation. *Journal of Ecology* 86, 738
- Bonasoni, P., Laj, P., Marinoni, A., Sprenger, M., Angelini, F., Arduini, J., Bonafè, U., Calzolari, F., Colombo, T., Decesari, S., Di Biagio, C., di Sarra, A.G., Evangelisti, F., Duchi, R., Facchini, M.C., Fuzzi, S., Gobbi, G.P., Maione, M., Panday, A., Roccatò, F., Sellegri, K., Venzac, H., Verza, G.P., Villani, P., Vuillemoz, E. and Cristofanelli, P. (2010). Atmospheric brown clouds in the Himalayas: first two years of continuous observations at the Nepal Climate Observatory-Pyramid (5079 m). *Atmospheric Chemistry and Physics* 10, 7515–7531
- Braungart, M., McDonough, W. and Bollinger, A. (2007). Cradle-to-cradle design: creating healthy emissions – a strategy for eco-effective product and system design. *Journal of Cleaner Production* 15(13–14), 1337–1348
- Bridbord, K. and Hanson, D. (2009). A personal perspective on the initial federal health based regulation to remove lead from gasoline. *Environmental Health Perspectives* 117(8), 1195–1201
- Camelley, T. and Le, X.C. (2001). *Correlation Between Chemical Characteristics and Biological Reactivity of Particulate Matter in Ambient Air*. Alberta. <http://environment.gov.ab.ca/info/library/6646.pdf>
- CBD (2010a). *Aichi Biodiversity Targets*. Secretariat of the Convention on Biological Diversity, Montreal. <http://www.cbd.int/sp/targets/>
- CBD (2010b). *Global Biodiversity Outlook 3*. Secretariat of the Convention on Biological Diversity, Montreal. <http://www.cbd.int/gbo3/ebook/>
- CDC (2012) *CDC's National Surveillance Data (1997–2009)*. US Centers for Disease Control and Prevention. <http://www.cdc.gov/nceh/lead/data/national.htm>
- CDC (2005). Blood lead levels: United States 1999–2002. *Morbidity and Mortality Weekly Report*, 54(20), 513–516
- CDC (2003). Blood lead levels: United States 1999–2002. *Morbidity and Mortality Weekly Report*, 52(SS-10)
- CDIAC (2010). Carbon Dioxide Information Analysis Center. <http://cdiac.ornl.gov/>
- Chang, Y.-C. and Wang, N. (2010). Environmental regulations and emissions trading in China. *Energy Policy* 38(7), 3356–3364
- COMEAP (2010). *The Mortality Effects of Long-Term Exposure to Particulate Air Pollution in the United Kingdom*. Committee on the Medical Effects of Air Pollutants. Health Protection Agency, United Kingdom
- Den Elzen, M. and Höhne, N. (2010). Sharing the reduction effort to limit global warming to 2° C. *Climate Policy* 10, 247–260
- Den Elzen, M. and Höhne, N. (2008). Reductions of greenhouse gas emissions in Annex I and non-Annex I countries for meeting concentration stabilisation targets. *Climatic Change* 91, 249–274
- EC (2011). Eurostat. <http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tsien110>
- EC (2008). *Directive 2008/50/EC on Ambient Air Quality and Cleaner Air for Europe*. <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:152:0001:0044:EN:PDF>
- EEA (2009). *NEC Directive Status Report of 2008*. EEA technical report 11/2009. European Environment Agency. <http://www.eea.europa.eu/publications/>
- Emberson, L.D., Büker, P., Ashmore, M.R., Mills, G., Jackson, L., Agrawal, M., Atikuzzaman, M.D., Corderby, S., Engardt, M., Jamir, C., Kobayashi, K., Oanh, K., Quadir, Q.F. and Wahid, A. (2009). A comparison of North American and Asian exposure-response data for ozone effects on crop yields. *Atmospheric Environment* 43(12), 1945–1953. doi:10.1016/j.atmosenv.2009.01.005
- ENA (2011). *The European Nitrogen Assessment: Sources, Effects and Policy Perspectives* (eds. Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., Van Grinsven, H. and Grizzetti, B.) Cambridge University Press. <http://www.nine-esf.org/ENA-Book>
- Forster, P., Ramaswamy, V., Artaxo, P., Bernsten, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M. and Van Dorland, R. (2007). Changes in atmospheric constituents and in radiative forcing. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L.). Cambridge University Press, Cambridge, and New York
- Fujino, J., Hibino, G., Ehara, T., Matsuoka, Y., Masui, T. and Kainuma, M. (2008). Back-casting analysis for 70% emission reduction in Japan by 2050. *Climate Policy* 8, S108–S124
- Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B. and Cosby, B.J. (2003). The nitrogen cascade. *BioScience* 53(4), 341–356
- Gould, E. (2009). Childhood lead poisoning: conservative estimates of the social and economic benefits of lead hazard control. *Environmental Health Perspectives* 117, 1162–1167
- Government of NCT of Delhi (2010). *State of the Environment Report for Delhi, 2010*. <http://www.delhi.gov.in/wps/wcm/connect/9e24b08042c37602aaafaa6c8168d2a2/SoE+Delhi+2010.pdf?MOD=AJPERES&lmod=301990690&CACHEID=9e24b08042c37602aaafaa6c8168d2a2>
- Grosse, S.D., Matte, T.D., Schwartz, J. and Jackson, R.J. (2002). Economic gains resulting from the reduction in children's exposure to lead in the United States. *Environmental Health Perspectives* 110(6), 563–569
- Hansen, J., Ruedy, R., Sato, M. and Lo, K. (2010). Global surface temperature change. *Reviews of Geophysics*. 48, RG4004. doi:10.1029/2010RG000345
- Hare, W.L., Cramer, W., Schaeffer, M., Battaglini, A. and Jaeger, C.C. (2011). Climate hotspots: key vulnerable regions, climate change and limits to warming. *Regional Environmental Change* 11, S1–S13. doi:10.1007/s10113-010-0195-4
- Hicks, W.K., Kuylenstierna, J.C.I., Owen, A., Dentener, F., Seip, H.M. and Rodhe, H. (2008). Soil sensitivity to acidification in Asia: status and prospects. *Ambio* 37, 295–303
- Hilton, F.G. (2006). Poverty and pollution abatement: evidence from lead phase-out. *Ecological Economics* 56(1), 125–131
- HTAP (2010). *Hemispheric Transport of Air Pollution, 2010. Part A: Ozone and Particulate Matter*. Air Pollution Studies No. 17. (eds. Dentener, F., Keating T. and Akimoto, H. Prepared by the Task Force on Hemispheric Transport of Air Pollution (HTAP) acting within the framework of the Convention on Long-range Transboundary Air Pollution (LRTAP) of the United Nations Economic Commission for Europe (UNECE). United Nations, New York and Geneva
- Hulme, M., Osborn, T.J. and Johns, T.C. (1998). Precipitation sensitivity to global warming: comparison of observations with HadCM2 simulations. *Geophysical Research Letters* 25, 3379–3382
- IJC (2010). *US and Canada Air Quality Agreement Progress Report*. International Joint Commission. www.ijc.org
- IMO (2009). *Second IMO GHG Study 2009* (eds. Buhaug, Ø., Corbett, J.J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Markowska, A.Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J.J., Wu, W., Yoshida, K.). International Maritime Organization, London
- IPCC (2011). Summary for Policymakers. In: *Intergovernmental Panel on Climate Change Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (eds. Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D., Ebi, K.L., Mastrandrea, M. D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M. and P.M. Midgley). Cambridge University Press, Cambridge and New York
- IPCC (2007). *Climate Change 2007: Synthesis Report*. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva
- IPCC (2005). *Carbon Dioxide Capture and Storage* (eds. Metz, B., Davidson, O., de Coninck, H., Loos, M. and Meyer, L.). IPCC Special Report. Cambridge University Press, Cambridge
- IPCC (2000). Summary for Policymakers: Emissions Scenarios. Special Report of IPCC Working Group III. Intergovernmental Panel on Climate Change. <http://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf>
- Kucera, V., Tidblad, J., Kreislova, K., Knotkova, D., Faller, M., Reiss, D., Sneath, R., Yates, T., Henriksen, J., Schreiner, M., Melcher, M., Ferm, M., Lefèvre, R.-A. and Kobus J. (2007). UN/ECE ICP materials dose-response functions for the multi-pollutant situation. *Water, Air and Soil Pollution Focus* 7, 249–258. doi:10.1007/s11267-006-9080-z
- Landrigan, P.J., Schechter, C.B., Lipton, J.M., Fahs, M.C. and Schwartz, J. (2002). Environmental pollutants and disease in American children: estimates of morbidity, mortality, and costs

- for lead poisoning, asthma, cancer, and developmental disabilities. *Environmental Health Perspectives* 110(7), 721–728
- Lanphear B.P., Hornung R., Khoury J., Yolton, K., Baghurst, P., Bellinger, D.C., Canfield, R.L., Dietrich, K.N., Bornschein, R., Greene, T., Rothenberg, S.J., Needleman, H.L., Schnaas, L., Wasserman, G., Graziano, J. and Roberts, R. (2005). Low-level environmental lead exposure and children's intellectual function: an international pooled analysis. *Environmental Health Perspectives* 113(7), 894–899
- Lawrence, D.M. and Slater, A.G. (2005). A projection of severe near-surface permafrost degradation during the 21st century. *Geophysical Research Letters* 32, L24401. doi:10.1029/2005GL025080
- Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S. and Schellnhuber, H.J. (2008). Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America* 105(6), 1786–1793. doi:10.1073/pnas.0705414105
- Levy, M.A., Haas, P.M. and Keohane, R.O. (1993). Improving the effectiveness of international environmental institutions. In *Institutions for the Earth: Sources of Effective International Environmental Protection* (eds. Haas, P.M., Keohane, R.O. and Levy, M.A.). MIT Press, Cambridge, MA
- Liu, J., Mauzerall, D.L., Horowitz, L.W., Ginoux, P. and Fiore, A.M. (2009a). Evaluating inter-continental transport of fine aerosols: (1) Methodology, global aerosol distribution and optical depth. *Atmospheric Environment*. doi:10.1016/j.atmosenv.2009.03.054
- Liu, J., Mauzerall, D.L. and Horowitz, L.W. (2009b). Evaluating inter-continental transport of fine aerosols: (2) Global health impacts. *Atmospheric Environment*. doi:10.1016/j.atmosenv.2009.05.032
- Lovei, M. (1998). *Phasing out Lead from Gasoline: Worldwide Experience and Policy Implications*. World Bank, Washington, DC
- Manney, G.L., Santee, M.L., Rex, M., Livesey, N.J., Pitts, M.C., Veefkind, P., Nash, E.R., Wohltmann, I., Lehmann, R., Froidevaux, L., Poole, L.R., Schoeberl, M.R., Haffner, D.P., Davies, J., Dorokhov, V., Gernandt, H., Johnson, B., Kivi, R., Kyrö, E., Larsen, N., Levelt, P.F., Makshtas, A., McElroy, C.T., Nakajima, H., Parrondo, M.C., Tarasick, D.W., von der Gathen, P., Walker, K.A. and Zinoviev, N.S. (2011). Unprecedented Arctic ozone loss in 2011. *Nature* 478, 469–475. doi:10.1038/nature10556
- MARPOL (2011). *International Convention for the Prevention of Pollution from Ships (MARPOL)*. <http://www.imo.org/about/conventions/listofconventions/pages/international-convention-for-the-prevention-of-pollution-from-ships-%28marpol%29.aspx>
- Menz, F.C. and Seip, H.-M. (2004). Acid rain in Europe and the United States: an update. *Environmental Science and Policy* 7(4), 253–265
- Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P. and Wilbanks, T.J. (2010). The next generation of scenarios for climate change research and assessment. *Nature* 463(7282), 747–756. doi:10.1038/nature08823
- NASA GISS (2011). *GISS Surface Temperature Analysis (GISTEMP)*. National Aeronautics and Space Administration Goddard Institute for Space Studies. <http://data.giss.nasa.gov/gistemp/>
- Nemet, G.F., Holloway T., and Meier, P. (2010). Implications of incorporating air-quality co-benefits into climate change policymaking. *Environmental Research Letters* 5, 014007. doi:10.1088/1748-9326/5/1/014007
- Newman P.A. and McKenzie, R. (2011). UV impacts avoided by the Montreal Protocol. *Photochemical and Photobiological Sciences* 10, 1152–1160, doi:10.1039/c0pp00387e
- Nilsson, J. and Grennfelt, P. (1988). *Critical Loads for Sulphur and Nitrogen*. Nordic Council of Ministers, Copenhagen
- NOAA GMD (2011a). Carbon Cycle Greenhouse Gases Group (CCGG). National Oceanic and Atmospheric Administration Global Monitoring Division (GMD). www.esrl.noaa.gov/gmd/ccgg
- NOAA GMD (2011b). NOAA Ozone Depleting Gas Index. National Oceanic and Atmospheric Administration Global Monitoring Division (GMD). <http://www.esrl.noaa.gov/gmd/odgi/>
- Nordhaus, W.D and Boyer, J. (2000). *Warming the World: Economic Models of Global Warming*. MIT Press
- NSIDC (2011). *NSIDC News*. National Snow and Ice Data Center, University of Colorado, Boulder. <http://nsidc.org/arcticseaicenews/>
- Peters, G.P., Minx, J.C., Weber, C.L. and Edenhofer, O. (2011a). Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences of the United States of America* 108(21), 8903–8908
- Peters, G.L., Marland, G., Le Quééré, C., Boden, T., Canadell, J.G. and Raupach, M.R. (2011b). Rapid growth in CO₂ emissions after the 2008–2009 global financial crisis. *Opinion and Comment, Nature Climate Change* 2, 2–4
- Polvani, L.M., Waugh, D.W., Correa, G.J.P. and Son, S.-W. (2011). Stratospheric ozone depletion: the main driver of 20th century atmospheric circulation changes in the southern hemisphere. *Journal of Climate* 24, 795–812
- Rasch, P.J., Crutzen, P.J. and Coleman, D.B. (2008). Exploring the geoengineering of climate using stratospheric sulfate aerosols: the role of particle size. *Geophysical Research Letters* 35, L02809
- Raupach, M.R. and Canadell, J.G. (2010). Carbon and the Anthropocene. *Current Opinion in Environmental Sustainability* 2, 210–218
- Raupach, M.R., Marland, G., Ciais, P., Le Quééré, C., Canadell, J.G., Klepper, G. and Field, C.B. (2007). Global and regional drivers of accelerating CO₂ emissions. *Proceedings of the National Academy of Sciences of the United States of America* 104(24), 10288–10293
- Rignot, E.I., Velicogna, M.R., van den Broeke, A., Monaghan, A. and Lenaerts, J. (2011). Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophysical Research Letters*, 38, L05503. doi:10.1029/2011GL046583
- RNMI (2010). *Monitoring Atmospheric Composition and Climate – Interim Implementation*. Royal Netherlands Meteorological Institute. http://www.temis.nl/macc/index.php?link=o3_msr_intro.html
- Rodhe, H., Langner, J., Gallardo, L. and Kjellstrom, E. (1995). Global scale transport of acidifying pollutants. *Water, Air, Soil Pollution* 85(1), 37–50
- Royal Society (2008). *Ground-level Ozone in the 21st Century: Future Trends, Impacts and Policy Implications*. Science Policy Report. <http://royalsociety.org>
- Schaefer, K., Zhang, T., Bruhwiler, L. and Barrett, A.P. (2011). Amount and timing of permafrost carbon release in response to climate warming. *Tellus B* 63(2), 165–180
- Schmid, O., Möller, W., Semmler-Behnke, M., Ferron, G.A., Karg, E., Lipka, J., Schulz, H., Kreyling, W.G., Stoeger, T. (2009). Dosimetry and toxicology of inhaled ultrafine particles. *Biomarkers* 14 Suppl 1:67-73. <http://www.ncbi.nlm.nih.gov/pubmed/19604063>
- Schneider, J.S., Huang, F.N., Vemuri, M.C. (2003). Effects of low-level lead exposure on cell survival and neurite length in primary mesencephalic cultures. *Neurotoxicology and Teratology* 25, 555–555
- Schwartz, J. (1994). Low-level lead exposure and children's IQ: a meta-analysis and search for a threshold. *Environmental Research* 65, 42–55
- Shindell, D., Kuylenstierna, J.C.I., Vignati, E., Van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S.C., Muller, N., Janssens-Maenhout, G., Raes, F., Schwartz, J., Faluvegi, G., Pozzoli, L., Kupiainen, K., Höglund-Isaksson, L., Emberson, L., Streets, D., Ramanathan, V., Hicks, K., Oanh, K., Milly, G., Williams, M., Demkine, V. and Fowler, D. (2012). Simultaneously mitigating near-term climate change and improving human health and food security. *Science* 335(6065), 183–189. doi:10.1126/science.1210026
- Shrestha, R.M., Pradhan S. and Liyanage, M. (2008). Effects of a carbon tax on greenhouse gas mitigation in Thailand. *Climate Policy* 8, S140–S155
- Shukla, P.R., Dhar, S. and Diptiranjan, M. (2008). Low-carbon society scenarios for India. *Climate Policy* 8, S156–S176
- Sitch, S., Cox, P.M., Collins, W.J. and Huntingford, C. (2007). Indirect radiative forcing of climate change through ozone effects on the land carbon sink. *Nature* 448(16), 791–795
- Smith, J.B., Schneider, S.H., Oppenheimer, M., Yohe, G.W., Hare, W., Mastrandrea, M.D., Patwardhan, A., Burton, I., Corfee-Morlot, J., Magazda, C.H.D., Fussler, H.M., Pittock, A.B., Rahman, A., Suarez, A. and van Ypersele, J.-P. (2009). Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) "reasons for concern". *Proceedings of the National Academy of Sciences* 106, 4133–413
- Stern, N. (2007). *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge and New York
- Stoddard, J.L., Jeffries, D.S., Lukewille, A., Clair, T.A., Dillon, P.J., Driscoll, C.T., Forsius, M., Johannessen, M., Kahl, J.S., Kellogg, J.H., Kemp, A., Mannio, J., Monteith, D.T., Murdoch, P.S., Patrick, S., Rebsdorf, A., Skjelkvale, B.L., Stainton, M.P., Traaen, T., van Dam, H., Webster, K.E., Wieting, J. and Wilander, A. (1999). Regional trends in aquatic recovery from acidification in North America and Europe. *Nature* 401(6753), 575–578
- Strachan, N., Foxon, T. and Fujino, J. (2008). Policy implications from the Low-Carbon Society (LCS) modelling project. *Climate Policy* 8, S17–S29
- Sunstein, C. (2007). Of Montreal and Kyoto: a tale of two protocols. *Harvard Environmental Law Review* 31(1), 1–66
- Thomas, V.M., Robert, H.S., James, J. and Thomas, G. (1999). Effects of reducing lead in gasoline: an analysis of the international experience. *Environmental Science and Technology* 33(22), 3942–3948
- Tsai, P.L. and Hatfield, T.H. (2011). Global benefits from the phaseout of leaded fuel – going unleaded. *Journal of Environmental Health* 74(5), 8–14
- UN (2000). *Millennium Development Goals*. <http://www.un.org/millenniumgoals/>
- UNCED (1992). *Agenda 21*. <http://www.un.org/esa/sustdev/documents/agenda21/english/Agenda21.pdf>
- UNDP/WHO (2009). *The Energy Access Situation in Developing Countries: A Review Focusing on the Least Developed Countries (LDCs) and Sub-Saharan Africa (SSA)*. UNDP, New York. http://content.undp.org/go/cms-service/stream/asset/?asset_id=2205620
- UNECE (2005). *The 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone*. Amended 2005. United Nations Economic Commission for Europe. <http://www.unece.org/fileadmin/DAM/env/lrtap/full%20text/1999%20Multi.E.Amended.2005.pdf>

- UNECE (1979). *Convention on Long-Range Transboundary Air Pollution (CLRTAP)*. <http://www.unece.org/fileadmin/DAM/env/lrtap/full%20text/1979.CLRTAP.e.pdf>
- UNEP (2012). *Reduction in Sulphur in Fuels. Partnership for Clean Fuels and Vehicles*. United Nations Environment Programme, Nairobi. <http://www.unep.org/transport/pcfvc/corecampaigns/campaigns.asp#sulphur> (accessed 23 March 2012)
- UNEP (2011a). *Bridging the Emissions Gap*. United Nations Environment Programme, Nairobi
- UNEP (2011b). *Global Status of Leaded Petrol Phase-Out*. United Nations Environment Programme, Nairobi. http://www.unep.org/transport/PCFV/PDF/MapWorldLead_January2011.pdf and <http://unep.org/transport/pcfvc/PDF/leadprogress.pdf> (accessed 26 May 2011)
- UNEP (2011c). *HFCs: A Critical Link in Protecting Climate and the Ozone Layer*. United Nations Environment Programme, Nairobi. <http://www.unep.org/climatechange/Publications/Publication/tabid/429/language/en-US/Default.aspx?ID=6224>
- UNEP (2010). *Environmental Effects of Ozone Depletion: 2010 Assessment*. United Nations Environment Programme, Nairobi
- UNEP (1987). *Montreal Protocol on Substances that Deplete the Ozone Layer*. Ozone Secretariat, United Nations Environment Programme, Nairobi. <http://ozone.unep.org/pdfs/Montreal-Protocol2000.pdf>
- UNEP (1985). *Vienna Convention for the Protection of the Ozone Layer*. Ozone Secretariat, United Nations Environment Programme, Nairobi. <http://ozone.unep.org/pdfs/viennaconvention2002.pdf>
- UNEP Ozone Secretariat (2011). Data Access Centre. http://ozone.unep.org/new_site/en/ozone_data_tools_access.php
- UNEP/WMO (2011). *Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers*. UNON/Publishing Services Section/Nairobi, ISO 14001:2004. http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_SDM.pdf
- UNFCCC (2012). *CDM in Numbers: Registration*. United Nations Framework Convention on Climate Change. <http://cdm.unfccc.int/Statistics/Registration/RegisteredProjByRegionPieChart.html>
- UNFCCC (2010). *Cancun Agreements*. <http://cancun.unfccc.int>
- UNFCCC (2009). *The Copenhagen Accord*. <http://unfccc.int/resource/docs/2009/cop15/eng/l07.pdf>
- UNFCCC (2008). *The Bali Action Plan*. <http://unfccc.int/resource/docs/2007/cop13/eng/06a01.pdf>
- UNFCCC (1998). *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. <http://unfccc.int/resource/docs/convkp/kpeng.pdf>
- UNFCCC (1992). *United Nations Framework Convention on Climate Change*. FCCC/INFORMAL/84 GE.05-62220 (E) 200705. <http://unfccc.int/resource/docs/convkp/conveng.pdf>
- USEPA (2010). *Protecting the Ozone Layer Protects Eyesights: A Report on Cataract Incidence in the United States Using the Atmospheric and Health Effects Framework Model*. US Environmental Protection Agency, Washington, DC. <http://www.epa.gov/ozone/science/effects/AHEFCataractReport.pdf>
- USEPA (2008). *National Ambient Air Quality Standards for Lead (Final Rule)*. US Environmental Protection Agency, Washington, DC. <http://www.epa.gov/oaqps001/lead/fr/20081112.pdf>
- Vahlsing, C. and Smith, K.R. (2010). Global review of national ambient air quality standards for PM₁₀ and SO₂ (24h). *Air Quality Atmosphere and Health*. doi:10.1007/s11869-010-0131-2
- Valavanidis, A., Fiotakis, K., Vlachogianni, T. (2008) Airborne particulate matter and human health: toxicological assessment and importance of size and composition of particles for oxidative damage and carcinogenic mechanisms. *J Environ Sci Health C Environ Carcinog Ecotoxicol Rev* 26(4):339-62 <http://www.ncbi.nlm.nih.gov/pubmed/19034792>
- van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C. Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J. and Rose, S.K. (2011). The representative concentration pathways: an overview. *Climatic Change* 109, 5–31
- Velders, G.J.M., Andersen, S.O., Daniel, J.S., Fahey, D.W. and McFarland, M. (2007). The importance of the Montreal Protocol in protecting climate. *Proceedings of the National Academy of Sciences of the United States of America* 104(12), 4814–4819
- Vestreng, V., Ntziachristos, L., Semb, A., Reis, S., Isaksen, I.S.A., and Tarrason, L. (2009). Evolution of NOx emissions in Europe with focus on road transport control measures. *Atmospheric Chemistry and Physics* 9, 1503–1520
- WHO (2012). Database: outdoor air pollution in cities. http://www.who.int/phe/health_topics/outdoorair/databases/en/index.html
- WHO (2011). *Health in the Green Economy: Health Co-benefits of Climate Change Mitigation – Housing Sector*. World Health Organization, Geneva
- WHO (2010). *Childhood Lead Poisoning*. World Health Organization, Geneva. <http://www.who.int/ceh/publications/leadguidance.pdf>
- WHO (2009). *Global Health Risks: Mortality and Burden of Disease Attributable to Selected Major Risks*. World Health Organization, Geneva. http://whqlibdoc.who.int/publications/2009/9789241563871_eng.pdf
- WHO (2006). *WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulphur Dioxide: Global Update 2005*. World Health Organization, Geneva
- WHO (2000). *Air Quality Guidelines for Europe*. Second Edition. WHO Regional Publications European Series No. 91. World Health Organization Regional Office for Europe, Copenhagen
- WHO (1999). *Air Quality Guidelines*. World Health Organization, Geneva
- Wilson, N. and Horrocks, J. (2008). Lessons from the removal of lead from gasoline for controlling other environmental pollutants: a case study from New Zealand. *Environmental Health* 7, 1. doi:10.1186/1476-069X-7-1
- WMO (2011). *Scientific Assessment of Ozone Depletion: 2010*. World Meteorological Organization Global Ozone Research and Monitoring Project Report No. 52. World Meteorological Organization, Geneva
- Wright, R.F., Larssen, T., Camarero, L., Cosby, B.J., Ferrier, R.C., Helliwell, R., Forsius, M., Jenkins, A., Kopacek, J., Majer, V., Moldan, F., Posch, M., Rogora, M. and Schopp, W. (2005). Recovery of acidified European surface waters. *Environmental Science & Technology* 39(3), 64A–72A
- WSSD (2002). *Johannesburg Plan of Implementation*. http://www.un.org/esa/sustdev/documents/WSSD_POI_PD/English/POIToc.htm
- Zhang, Z.X. (2010). *China in the Transition to a Low Carbon Economy*. East-West Centre Working Papers. Economics Series 109
- Zhao, Y., Duan, L., Xing, J., Larssen, T., Nielsen, C.P. and Hao, J.M. (2009). Soil acidification in China: is controlling SO₂ emissions enough? *Environmental Science & Technology* 43(21), 8021–8026