chapter twelve

Air pollution

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Introduction

Outdoor air pollution poses a considerable threat to the environment as well as to human health, leading to illness and premature death. Fortunately, considerable progress has been made over the past decades in reducing air pollution, although important challenges remain. This chapter will review the main successes (and some failures) of these efforts to control air pollution, focusing on their impact on human health.

Adverse effects of different pollutants on human health have been well documented in Europe and other parts of the world (Katsouyanni et al. 2007; Medina et al. 2009; WHO Regional Office for Europe 2004). Awareness of these health effects was boosted by a number of disastrous events, particularly the Great Smog in London in December 1952. Stagnant weather conditions caused a sharp increase in the concentration of air pollutants, and more than three times as many people died than would have been expected under normal conditions. This and other similar events have led not only to advances in air pollution control but also to research that has increased considerably our understanding of the health effects of air pollution (Brunekreef and Holgate 2002).

Initially, research focused on sulphur dioxide and 'black smoke'. These are released during the combustion of traditional fossil fuels such as coal and were the main culprits of the London Great Smog. In the late 1970s, however, air pollution from these sources had diminished greatly, at least in many parts of western Europe, as a result of shifts to other fuels as well as effective abatement measures (as noted below, Dublin was one exception; Kelly and Clancy 1984; Clancy et al. 2002). Around that time other components of air pollution were identified to be of concern and hence widely used to characterize air quality (Brunekreef and Holgate 2002): nitrogen oxides (produced by the ever-rising number of motor vehicles), ozone (produced by the action of sunlight on nitrogen dioxide and hydrocarbons during warm and sunny weather) and small airborne particles (fine particulate matter: particulate matter of less than 10 μm (PM10) or even 2.5 μm (PM2.5); some emitted directly during combustion of diesel and other fuels and some formed in the atmosphere from oxidation and transformation of primary gaseous emissions). These three components now constitute the most problematic pollutants in terms of causing harm to health. The key emission sources are energy production in power plants, industry and households, and road transport.

Exposure to ambient air pollution has been linked to a number of different health outcomes. Most obviously, this affects the respiratory system but there is also growing evidence of effects on the cardiovascular system (Pelucchi et al. 2009; Brook et al. 2010). Both short- and long-term effects have been found. A selection of some of the most important health effects linked to specific pollutants is summarized in Table 12.1. Outdoor air pollution is estimated to account for 2.5% of deaths in high-income countries and 0.8% of DALYs (World Health Organization 2009).

One of the most important contributors to the overall health burden is long-term exposure to fine particulate matter. This has been estimated to reduce life expectancy by a year or more in the Netherlands, a country with particularly high exposure to this form of air pollution (Brunekreef 1997). In Europe as a whole (excluding the former USSR, but including the Baltic states), pollution

Table 12.1 A selection of important health effects linked to specific pollutants

Pollutant	*Effects related to short-term exposure*	*Effects related to long-term exposure*
Particulate matter	Lung inflammatory reactions, respiratory symptoms, adverse effects on the cardiovascular system, increase in medication usage, increase in hospital admissions, increase in mortality	Increase in lower respiratory symptoms, reduction in lung function in children and adults, increase in chronic obstructive pulmonary disease, reduction in life expectancy mainly from cardiopulmonary disorders and lung cancer
Ozone	Adverse effects on pulmonary function, lung inflammatory reactions, adverse effects on respiratory symptoms, increase in medication usage, increase in hospital admissions, increase in mortality	Reduction in lung function development
Nitrogen dioxide[a]	Effects on pulmonary function particularly in asthmatics, increase in airway allergic inflammatory reactions, increase in hospital admissions, increase in mortality	Reduction in lung function, increased probability of respiratory symptoms

Source: WHO Regional Office for Europe 2004
Note: [a]In ambient air, nitrogen dioxide serves as an indicator for a complex mixture of mainly traffic-related pollutants

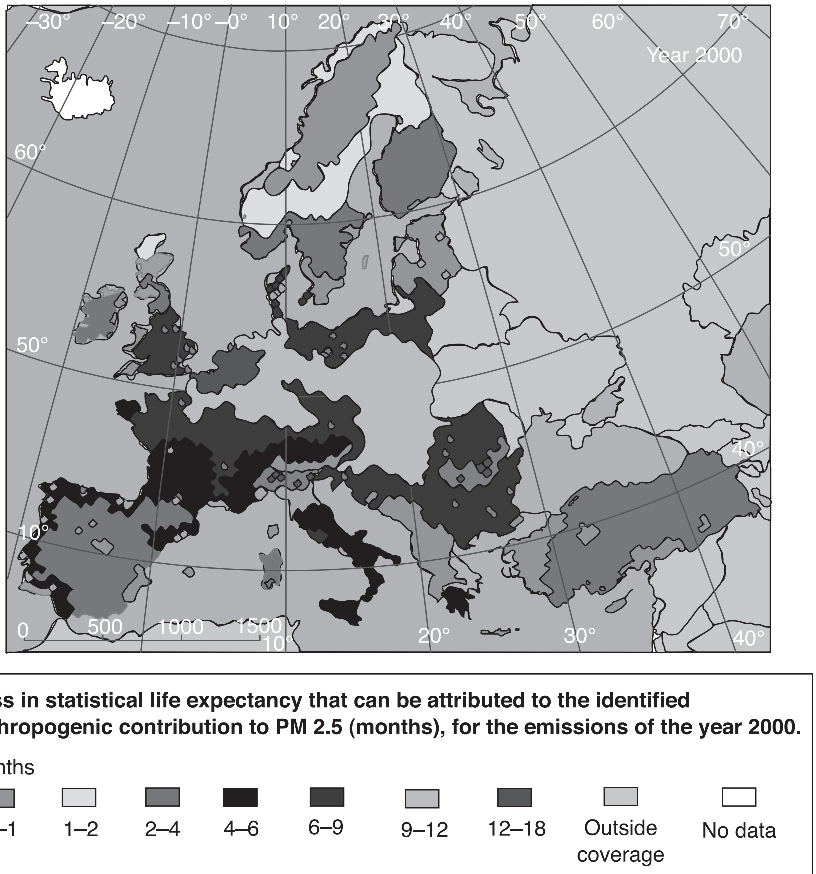


Figure 12.1 Loss of average life expectancy (in months) attributable to exposure to fine particulate matter ($PM_{2.5}$) in 2000

Source: European Environment Agency 2010a

by PM2.5 causes 500,000 premature deaths per year, corresponding to an estimated 5 million years of life lost (European Environment Agency 2010a). As Fig. 12.1 shows, reductions in life expectancy attributable to PM2.5 in air are concentrated in some of the most heavily urbanized and industrialized parts of Europe. Exposure to ozone concentrations exceeding critical levels for health is associated with more than 20,000 premature deaths in the EU-25 annually (European Environment Agency 2010a). Similar estimates are not available for nitrogen oxides or sulphur dioxide.

Children seem particularly sensitive to some pollutants. Other groups that are more sensitive include the elderly, those with cardiorespiratory disease and people in lower socioeconomic groups. Epidemiological studies have been unable to establish threshold levels below which no adverse health effects of air pollution occur (WHO Regional Office for Europe 2004).

Effectiveness of air pollution control policies

Emissions of air pollutants occur as a result of almost all economic and societal activities; consequently, increases in economic activity and population numbers are important drivers of increases in emissions. Over the past decades, however, it has been possible to partly decouple emission developments from economic growth, both by improving energy efficiency in the production of goods and services and by reducing emissions relative to the amount of energy consumed (European Environment Agency 2010b).

Emission reduction has been achieved by a variety of means and has depended, to a large extent, on international collaboration. Such collaboration has played a larger role in this area than in many other areas of health policy. The reasons are that both the health threats and the countermeasures transcend national borders. Air pollution from power plants drifts across country borders; vehicles that may or may not be subject to emission regulations are produced in one country and driven in another; and, in a globalizing world, industries demand a level playing field created by internationally agreed norms and regulations.

The main countermeasures taken in the period 1970–2010 are briefly summarized and their effectiveness in reducing the four main components of air pollution and their associated health impacts is reviewed.

Sulphur dioxide

Sulphur dioxide is emitted when fuels with a high sulphur content, such as coal and heavy fuel oils, are burnt. Emissions can be reduced by shifting to other fuels with lower sulphur content, such as natural gas, or by capturing sulphur dioxide before it is released into the air. The main source of sulphur dioxide emissions since the 1970s has been industry (including the energy sector).

In the 1970s, it became clear that countries' exposures to sulphur dioxide air pollution, for example in the form of 'acid rain', were strongly dependent on their neighbours' emissions and, in 1979, the United Nations Economic Commission for Europe established a *Convention on Long-range Transboundary Air Pollution*. Over the years, several protocols have been adopted to reduce sulphur emissions. In addition to these United Nations protocols, several EU Directives have been implemented on the regulation of sulphur emissions, focusing on ceilings for sulphur emissions during combustion of fuels in power plants and industry and on the sulphur content of fuels (Vestreng et al. 2007).

Within these agreements, countries also agreed to exchange harmonized information on their emissions and to have their data validated. Consequently, we are now rather well informed about trends, particularly since about 1980. Historical data show that, in Europe, total sulphur dioxide emissions rose steeply until 1980, when a peak was reached and an equally steep decline began (Fig. 12.2). In 2004, total emissions were less than a third of those in 1980. Three periods of emission reduction have been identified. The period 1980–1989 was characterized by low annual emission reductions for Europe as a whole, with emission reductions occurring mainly in western Europe. No international protocols were as yet in place, but western European countries

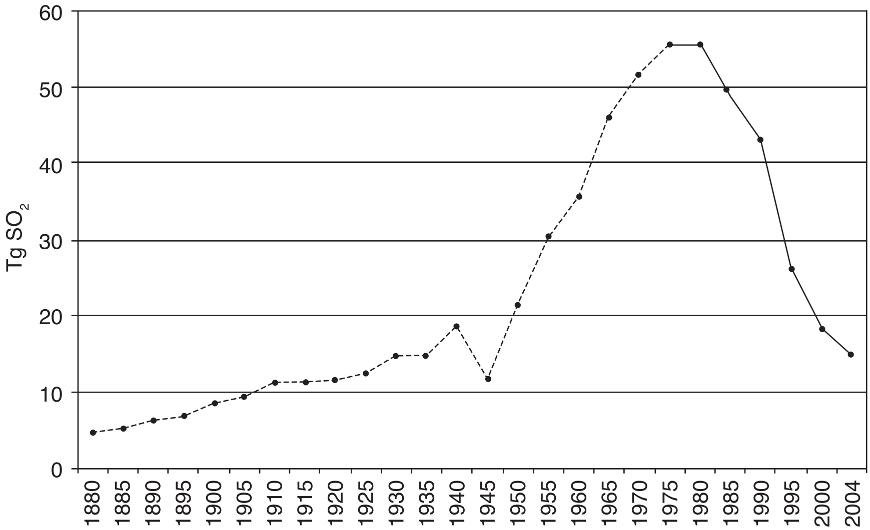


Figure 12.2 Historical development of sulphur dioxide emissions in Europe

Source: Vestreng et al. 2007

Note: Tg: teragram = 10^{12} gram = mega tonne

had already started to implement new technologies and fuels. In central and eastern Europe, emissions still were on the rise (Vestreng et al. 2007).

The period 1990–1999, by comparison, was characterized by large annual emission reductions for Europe as a whole, reflecting emission reductions in both western and central and eastern Europe. International protocols were in place that stimulated western European countries to continue their efforts to reduce pollutants. In central and eastern Europe, reductions occurred first as a result of the economic recession and the closing down of old heavy industries; when activity levels started to increase again, however, new technologies were implemented, which helped to keep emissions down. The annual emission reductions in the period 2000–2004 are again lower, with equally large reductions in both eastern and western countries (Vestreng et al. 2007). Since then emissions have continued to fall, although there is an increasing number of countries with year-to-year increases in sulphur emissions.

The effectiveness of these policies is evident from the fact that current sulphur dioxide emission levels are considerably below the level that would have been expected if they had been determined by trends in economic activity only, without concerted European policies. Reduced emissions have also led to reduced atmospheric concentrations of sulphur dioxide (European Environment Agency 2010a,b).

Particulate matter

The key anthropogenic sources of particulate matter and its precursors are road vehicles and industrial installations. Since 1990, the EU regulates exhaust emissions for both light- and heavy-duty vehicles and has gradually lowered the permissible emission limits. As a result, substantial declines in particulate matter emissions from vehicles have occurred since the end of the 20th century despite a large increase in the number of vehicles and total traffic activity over the same period. Emissions from industry of particulate matter and their precursors have also declined as a result of EU Directives on emissions (European Environment Agency 2011). In 2005, total road traffic particulate matter emissions were 63% lower than they would have been in the absence of EU standards, and a similar effect size was estimated for industry-related emissions-limiting directives (European Environment Agency 2010a,b).

Long-term trend data on particulate matter air concentrations are not available as methods of measurement have changed over time. Harmonized data covering Europe as a whole have only been available since 1999, and these data, surprisingly, show small and inconsistent reductions, perhaps as a result of measurement problems (European Environment Agency 2011). It is unclear, therefore, whether population health can have improved much as a result of measures to control particulate matter emissions.

Nitrogen oxides

Road transport has been the dominant source of nitrogen oxides emissions since the 1970s. Protocols and directives of the United Nations Economic Commission for Europe and the EU have set increasingly ambitious emissions ceilings for nitrogen oxides, both for individual vehicle types and at the national level. These stimulated the implementation of technological improvements to vehicles that can reduce emissions, such as improved combustion and the fitting of catalytic convertors.

Long-term trend data on nitrogen oxides emissions for Europe as a whole show a substantial increase during most of the 20th century until a major turning point was reached around 1990, after which emissions have declined (Fig. 12.3). Between 1950 and 1980, the steep rise in emissions was a result of a steep upward trend in liquid fuel use. Between 1980 and 1990, the rise in emissions became less steep, partly as a result of a slowing in the rate of growth of fuel consumption after the first oil crisis in western Europe, and of decreased fuel consumption in many central and eastern European countries.

It was only after 1990 that the effect of emission reduction policies set in. Improved vehicle technologies and stringent inspection systems reduced nitrogen oxides in road traffic emissions in the period 1990–2000 in western Europe, despite economic growth and increases in fuel consumption.

In central and eastern Europe, emissions declined in this period as well, but as a result of the economic crisis and of imports of cleaner cars from western Europe. After 2000, emissions in Europe as a whole continued to decrease, but less steeply because the economic recovery in eastern Europe increased emissions from road traffic in this region (Vestreng et al. 2009).

Long-term trend data on nitrogen oxides concentration in air are not available, but trends since 1999 show a consistent decline in average concentrations as well as in the proportion of urban populations exposed to limit levels set for protecting human health (European Environment Agency 2011).

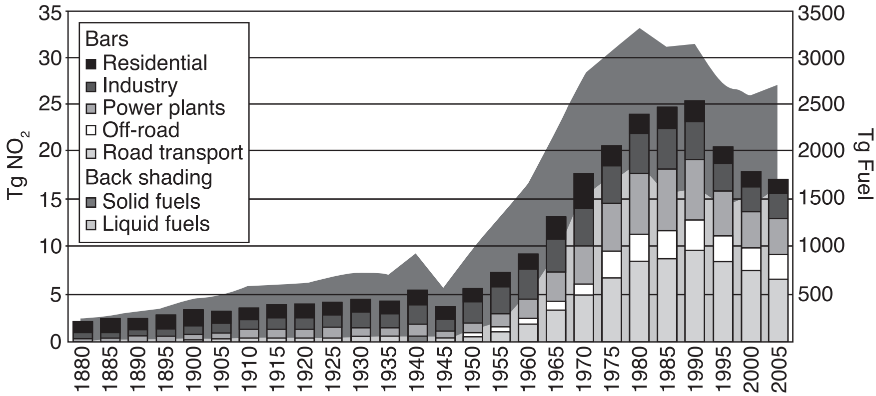


Figure 12.3 Historical trends of nitrogen oxides emissions in Europe (in teragrams)

Source: Vestreng et al. 2009

Note: Tg: teragram = 10^{12} gram = mega tonne

Ozone

Ground-level ozone is not directly emitted into the atmosphere but formed from a chain of chemical reactions following emissions of precursor gases, including nitrogen oxides (see above). Policy measures to reduce ozone concentrations mainly target emissions of these precursors, and many of the United Nations and EU Directives mentioned above are, therefore, also relevant for the reduction of ozone concentrations. In addition, the EU has set specific standards for exposure to ozone in its 2008 Air Quality Directive (European Environment Agency 2011).

Long-term trends of ozone concentrations can only be assessed for a limited number of European countries, mainly in western Europe. Since the early 1990s, when only a few measurement sites were available, the number of days in which ozone concentrations exceeded a maximum value (120 $\mu g/m^3$) has declined in most of the sites. By the end of the 1990s, many more locations were producing data than in the earlier years and they covered a larger area of Europe. Since then, most stations reported fewer episodes when the daily threshold was exceeded, although some recorded an increase, mainly in southern and central Europe. Annual mean concentrations of ozone, however, do not show a consistent downward trend (European Environment Agency 2011).

Successes and failures of air pollution control in Europe

Health impacts

Estimates of the overall health impact of the measures described above are scarce. The massive reductions in sulphur dioxide concentrations must have had a positive impact on European population health, but the magnitude of this impact is not precisely known. This is because the reductions in sulphur dioxide have coincided with rising estimates of the impact of sulphur dioxide on health, suggesting that sulphur dioxide was a marker for other compounds that have changed over time (Brunekreef and Holgate 2002).

Within the Aphekom project (www.aphekom.org) a study undertaken in 20 cities across Europe, aiming to assess the impact of the implementation of EU legislation on sulphur content in certain liquid fuels over the period 1990–2004, it was found there was a general downward trend without any stepwise changes coinciding with the introduction of specific directives. Concentrations were relatively high in Athens and Budapest throughout the study period, but even in those cities concentrations declined substantially. In this project, no changes in the impact of sulphur dioxide on health outcomes over time were observed, and it was estimated that the reductions in sulphur dioxide levels prevented more than 2000 deaths per year in the 20 cities starting in the year 2000 compared with levels prior to October 1994 (A. Le Tertre et al. 2012 (manuscript submitted for publication).

Trends in air concentrations of particulate matter and ozone over the period 1970–2010 have been unclear, but air concentrations of nitrogen oxides have almost certainly decreased substantially. Taken together, there must have been a positive net effect on population health, even though its magnitude is not precisely known. It has been estimated that EU air emission policies reduced the negative health impact of the road transport sector in Europe as a whole (measured in terms of years of life lost) by 13% and 17% through reduced emissions of PM2.5 and ozone, respectively. Similarly, the negative health impact of the industrial sector was reduced by 60% by 2005 through reduced emissions of PM2.5 compared with a non-policy scenario (European Environment Agency 2010a,b).

Although many of the air pollution control policies were coordinated internationally, there have been considerable between-country differences in progress against these health hazards. A few of these specific successes will be highlighted, together with some international comparative data.

Selected national and local successes

The reunification of the German Democratic Republic and the Federal Republic of Germany in 1990 was accompanied by marked changes in the political environment, in socioeconomic structures and in air pollution controls (Henschel et al. 2012). Between 1989 and 1991, an immediate and remarkable fall in pollutant emissions was observed (Ebelt et al. 2001). These rapid and favourable trends continued throughout the 1990s as a result of a shift from brown coal to natural gas as the major energy source for industries, power plants and domestic space heating (Peters et al. 2009)l; there were also changes in the composition of the vehicle fleet, for example a shift from cars with a two-stroke motor to cars having three-way catalytic converters (Ebelt et al. 2001). Within a decade, ambient air pollution in the former German Democratic Republic converged with levels in the former Federal Republic of Germany (Sugiri et al. 2006). Although some studies were unable to find a short-term effect of improved air quality on mortality (Breitner et al. 2009; Peters et al. 2009), other studies found that differences in lung function among children aged five to seven years between cities of the former German Democratic Republic and the former Federal Republic of Germany vanished simultaneously with the reduction in air pollution (Sugiri et al. 2006), and that bronchitic symptoms decreased (Frye et al. 2003).

Dublin, the capital of Ireland, experienced extreme air pollution episodes during the 1980s, mainly through a shift from the use of oil for space heating to cheaper solid fuel, particularly bituminous coal and peat (Henschel et al. 2012). This shift occurred because of the policy of the Irish Government to reduce dependence on imported oil following the 1970 world oil crisis (Goodman and Clancy 2002). Marked increases in respiratory deaths at a main Dublin hospital in 1982 were associated with an extraordinarily severe episode (Kelly and Clancy 1984). Eventually the government had to take action to improve air quality; in September 1990 the marketing, sale and distribution of coal was banned in Dublin. An immediate fall in air pollution levels was observed with implementation of the ban (Medina et al. 2002, pp. 217–219), and mortality from respiratory and cardiovascular causes also declined substantially (Clancy et al. 2002). Following the success of this intervention, the ban was extended stepwise to 11 other Irish cities (Goodman et al. 2009). The first city to follow was Cork, and here too both air pollution and mortality levels declined simultaneously with implementation of the ban (Goodman et al. 2009; Rich et al. 2009).

London, one of the world's megacities, with approximately 8 million inhabitants, suffered from major traffic congestion from the 28 million journeys made on each day into and out of the city. On 17 February 2003, the traffic Congestion Charging Scheme was launched, with its main objective to reduce traffic congestion in the central area of the city by charging, initially, £5 (€6) daily, increased to £8 (€9.60) in 2005, for each four-wheeled vehicle entering the area on weekdays. At the same time, further measures were taken to improve traffic flow in London, such as bus network improvements and improvements of walking and cycling schemes (Transport for London 2006). After one year, a traffic volume reduction of 18% and a congestion reduction of 30% were observed (Transport for London 2004; Henschel et al. 2012). No clear changes in air quality were observed (Tonne et al. 2008; Kelly et al. 2011a). There were also some changes in the composition of PM10, such as lower levels of copper, zinc and bioavailable iron, thought to result from reductions in brake and tyre use (Kelly et al. 2011b). Some (small) health benefits are likely to have been achieved as well. The estimated years of life gained per 100,000 population were predicted to be 26 years for Greater London and 183 years for residents within the wards covered by the Congestion Charging Scheme (Tonne et al. 2008). There was also a suggestive decline in hospital admissions for bronchiolitis (Tonne et al. 2010).

In Stockholm, capital and largest city of Sweden, a similar congestion charging scheme trial was found to reduce air pollution levels in the inner city area. Taking nitrogen dioxide as a marker for traffic emissions, a population health impact of 206 years of life gained per 100,000 people for the area of Greater Stockholm over a 10-year period was calculated, assuming that the decrease of the exposure level would persist (Johansson et al. 2009).

Between-country variations

As shown in Table 12.2, there have been substantial differences between countries in the extent and timing of their sulphur dioxide emission reductions. In 2004,

Table 12.2 Sulphur dioxide emission trends in European countries, 1980–2004

Country	*Sulphur dioxide emission (Gg)*					
	1980	*1985*	*1990*	*1995*	*2000*	*2004*
Albania	72	73	74	14	32	32
Armenia	141	100	86	15	11	8
Austria	344	179	74	47	32	29
Azerbaijan	603	543	615	260	162	130
Belarus	740	690	888	344	162	97
Belgium	828	400	361	262	171	154
Bosnia and Herzegovina	482	483	484	360	420	427
Bulgaria	2,050	2,314	2,007	1,477	918	929
Croatia	150	164	178	70	60	85
Cyprus	28	35	46	41	51	45
Czech Republic	2,257	2,277	1,876	1,090	264	227
Denmark	450	333	176	133	27	23
Estonia	287	254	274	117	96	90
Finland	584	382	259	95	74	83
France	3,216	1,496	1,333	968	613	484
Georgia	230	273	43	6	7	5
Germany	7,514	7,732	5,289	1,708	630	559
Greece	400	500	487	536	493	537
Hungary	1,633	1,404	1,011	705	486	240
Iceland	18	18	9	9	9	9
Ireland	222	140	186	161	131	71
Italy	3,437	2,045	1,795	1,320	755	496
Kazakhstan	639	575	651	528	506	425
Latvia	96	97	97	47	10	4
Lithuania	311	304	263	92	43	40
Luxembourg	26	26	26	7	4	4
Malta	29	29	29	33	26	17
Netherlands	490	258	189	127	72	66
Norway	136	91	53	34	27	25
Poland	4,100	4,300	3,278	2,381	1,507	1,286
Portugal	266	198	317	332	306	203
Republic of Moldova	308	282	175	94	13	15
Romania	1,055	1,255	1,310	882	727	685

Country	*Sulphur dioxide emission (Gg)*					
	1980	*1985*	*1990*	*1995*	*2000*	*2004*
Russian Federation	7,323	6,350	6,113	3,101	2,263	1,858
Serbia and Montenegro	406	478	593	428	396	341
Slovakia	780	613	542	239	127	97
Slovenia	234	241	198	127	99	55
Spain	3,024	2,542	2,103	1,809	1,479	1,360
Switzerland	491	266	117	79	52	47
The former Yugoslavian Republic of Macedonia	107	109	110	93	90	87
Turkey	1,030	1,345	1,519	1,397	2,122	1,792
Ukraine	3,849	3,463	3,921	2,342	1,599	1,145
United Kingdom	4,838	3,714	3,699	2,343	1,173	833
Total	**55,340**	**48,448**	**42,896**	**26,282**	**18,263**	**15,162**

Source: Vestreng et al. 2007

Note: Gg: Gigagram = 10^9 grams

the grand total for all countries in the table was a reduction to 25% of the sulphur dioxide emissions in 1980; however, in several countries the reductions were considerably lower, such as Bulgaria, Croatia, Estonia, Portugal, Romania, the Russian Federation and Spain. Greece even saw its emissions increase over this period. While some of these developments are likely to reflect a catch-up in economic growth or in road traffic volume, the examples of the Czech Republic and Poland show that such growth can be combined with substantially reduced emissions (Vestreng et al. 2007).

Reductions in emissions of nitrogen oxides have also differed substantially among countries. Policy measures involved new standards for technological improvements to vehicles, and while the automobile industry has dutifully complied with these regulations, the speed with which they have impacted on actual pollution levels is largely dependent on the pace of turnover of the vehicle fleet. While average passenger car fleet emissions in Germany and Switzerland reached emission standards within five years of their introduction, Spain, with a rather old vehicle fleet, took more than ten years. A comparison of estimated nitrogen oxides emission between western and central and eastern Europe shows that the average passenger car in central and eastern Europe has up to ten times higher emissions than its equivalent in western Europe. Similar differences, but of a lesser magnitude, are found for light- and heavy-duty vehicles (Vestreng et al. 2009).

It is not surprising, therefore, that air pollution concentrations also differ substantially between European countries (Fig. 12.4). High concentrations of sulphur dioxide are mainly found in central and eastern Europe. High concentrations of particulate matter are found in these countries as well, but are also found in the north of Italy and in some urban and industrial centres in the rest of western Europe. High concentrations of nitrogen dioxide are found

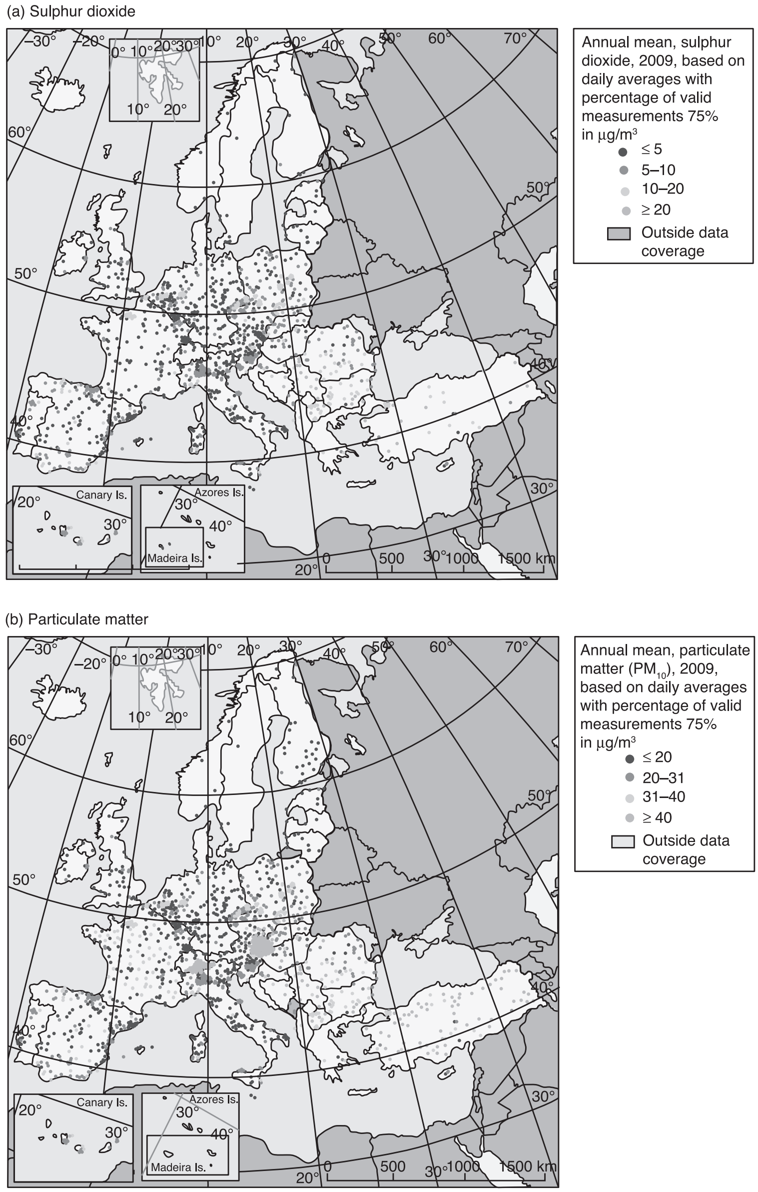
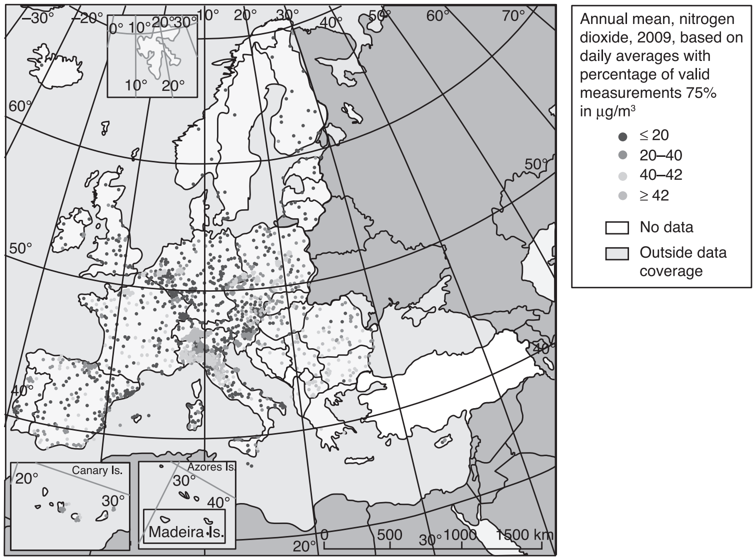


Figure 12.4 Geographical distribution of air pollutant exposure in Europe. (a) Sulphur dioxide. Dark orange dots refer to places where the limit value of 20 µg/m³ for protection of vegetation is exceeded. (b) Particulate matter (PM_{10}). Dark orange dots refer to places where the annual value of 40 µg/m³ set in the European Union 2005 Air Quality Directive is exceeded; light orange where the statistically derived 24-hour limit of 31 µg/m³ is exceeded; pale green where the WHO air quality guidance value for PM_{50} of <50 µg/m³ is exceeded; and dark green where concentrations below the WHO air quality guidance value for PM_{10} is achieved.

Source: European Environmental Agency 2011

(c) Nitrogen oxides



(d) Ozone

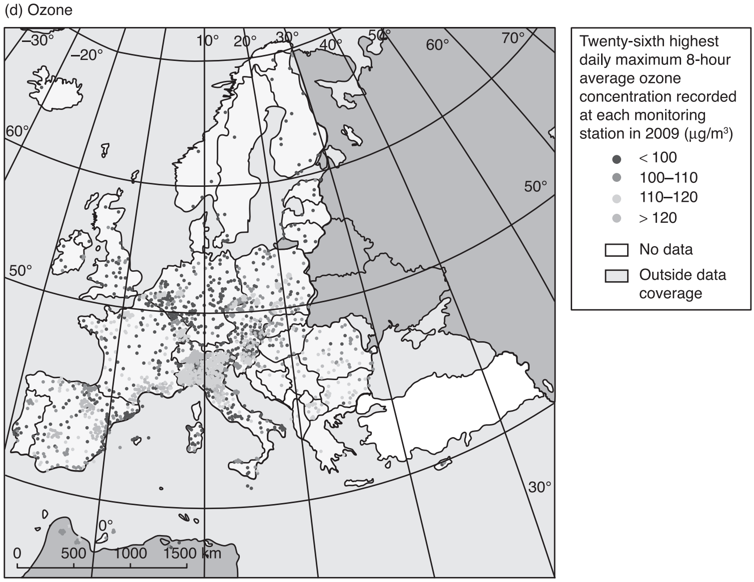


Figure 12.4 contd. (c) Nitrogen oxides. Light orange dots refer to places that exceed the annual limit value of 40 µg/m³; dark orange where places exceed this limit plus the margin of tolerance (i.e. 42 µg/m³). (d) Ozone, as 8-hour average recorded values. Dots show the proximity to meeting the target value. Dark orange dots show the 26th highest daily values exceeding the 120 µg/m³ threshold, implying exceeding the target values

Source: European Environmental Agency 2011 in urban centres across Europe. High levels of ozone air pollution are found in a zone stretching from the east coast of Spain across the south of France and Italy into central and eastern Europe (European Environment Agency 2011).

Discussion and conclusions

Air pollution is one among many causes of cardiorespiratory disease. Unlike, say, cigarette smoking, where exposure can be measured relatively easily in terms of the number of packs smoked over a period of years, individual exposure to ambient air pollution is much more difficult to measure. Also, while there are extensive time-series data on some of the more visible pollutants, the dangers posed by invisible ones, such as fine particulate matter, have only been appreciated much more recently. Furthermore, and again unlike cigarette smoking, there are no specific health outcomes for air pollution, but these occur across a range of conditions and causes of death. Consequently, the health effects of air pollution control are difficult to quantify.

The picture painted in this chapter is a mixed one. There have been some clear successes, such as the reductions in sulphur dioxide and nitrogen oxides, which must have produced substantial health gains. Yet the situation with regard to particulate matter and ozone is less clear, although particulate matter concentrations are likely to have gone down considerably since the 1950s. The picture is also mixed geographically. Countries in western Europe have been much more successful in reducing emissions than those in central and eastern Europe, and at least some of the reductions in the latter countries are incidental to the closure of highly polluting factories on economic rather than health grounds.

Overall, emission levels are a product of the volume of material emitted into the atmosphere and the concentration of pollutants within it. The successes observed are primarily a result of technological advances, such as catalytic converters in motor vehicles, or changes in the type of fuel being used, rather than the amount of material being emitted, which has tended to increase with economic growth. This should give rise to concern for the future. Even leaving aside concerns about emissions of greenhouse gases, not considered in this chapter, the scope for further advances in cleaning the products of burning fossil fuels may be limited. It cannot, therefore, be assumed that the gains seen in recent decades will continue at the same pace.

There is an important lesson from these experiences. Air pollution is characterized by externalities, and those who produce the pollution do not normally have to pay for the damage it causes. Consequently, it is not possible to leave it to the market to control. As the examples in this chapter show, success has been brought about by regulation, frequently acting as a spur for technological innovation. Moreover, the cross-border nature of pollution means that this is not an issue that can be addressed by any country on its own. Although this is perhaps the most obvious example of where concerted international regulatory action is needed to safeguard health, it is not the only one, something that will be discussed in subsequent chapters.

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