CHAPTER 2. GEOGRAPHICAL DISTRIBUTION OF AIR POLLUTANTS

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In terms of constituents, air pollution has very wide geographical variation and represents many different entities. The proportion of the pollution mix, as well as the levels (concentrations) of the various pollutants, also may vary. However, the information that is available to characterize the air pollution mix is quite limited. Some pollutants or mixtures (e.g. particulate matter [PM]) are measured routinely in many parts of the world, while others are not, although some indication of their levels is available. In addition, air pollution may contain harmful substances of which nothing is known.

Recent scientific evidence, derived mainly from studies in Europe and North America, consistently suggests that urban air pollution causes adverse health effects (WHO, 2003). In the World Health Organization (WHO) Global Burden of Disease project, it has been estimated that urban air pollution worldwide, as measured by concentrations of PM, causes about 5% of all mortality attributable to cancers of the trachea, bronchus, and lung (Cohen *et al.*, 2004). The burden in terms of absolute numbers occurs predominantly in developing countries, but in proportional terms, some of the most affected regions include parts of Europe.

To justify the evaluation of the effects of any environmental exposure within the framework of WHO, it is useful to demonstrate the extent of the exposure and, consequently, of the global public health problem. In addition, a satisfactory characterization of the air pollution mix linked with estimated health effects gives valuable information on the importance of such effects in relation to the various constituents.

Information from different projects that demonstrate the geographical distribution and variability of air pollutants worldwide, in Europe, and in the USA is compiled below.

Which pollutants?

In many parts of the world, monitoring systems for air pollutants have been installed, usually within the framework of governmental regulatory programmes. The older and most extensive of these are in North America and the European Union. The pollutants most frequently monitored are: (i) the gases: sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone, and carbon monoxide; and (ii) the PM indicators: total suspended particles, black smoke, PM < 10 µm (PM_{10}), and PM < 2.5 µm ($PM_{2.5}$). Data from other parts of the world are available, but access to these and standardization of the monitoring methods are limited (Cohen *et al.*, 2004). Measurements for other pollutants, most frequently constituents of PM, have been undertaken within the framework of specific studies and often provide valuable information on their geographical distribution. However, studies including the investigation of effects of PM constituents tend to be limited in time and seasonal coverage and often concern few areas and few points (often one point) within the areas studied. Generally, they are designed and performed to meet the needs of research projects and not to regularly monitor concentrations of pollutants. Examples of such projects in Europe are the Air Pollution Exposure of Adult Urban Populations in Europe Study (EXPOLIS), the Exposure and Risk Assessment for Fine and Ultrafine Particles in Ambient Air Study (ULTRA), the Relationship between Ultrafine and Fine Particulate Matter in Indoor and Outdoor Air Project (RUPIOH), the Chemical and Biological Characterization of Ambient Air Coarse, Fine and Ultrafine Particles for Human Health Risk Assessment Project (PAMCHAR), and the Air Pollution and Inflammatory Response in Myocardial Infarction Survivors Gene–Environment Interactions in a High-Risk Group Project (AIRGENE).

More information is available on the pollutants that are measured routinely. Since much of the evidence on the harmful health effects of air pollution is focused on the concentrations of PM, attention is being diverted there. Consequently, little information is available on the geographical distribution of specific carcinogens that are more interesting in the present context.

Table 2.1 shows the number of cities for which data on PM (measured as either total suspended particles or PM_{10}) are available, by region of the world. It can be seen that the monitoring systems are much more widespread in North America and Europe.

Worldwide distribution of air pollutants

Fig. 2.1 shows the estimated annual average concentrations of PM_{10} in cities with populations > 100 000 and in national capitals. Table 2.2 gives the numbers represented in Fig. 2.1, which were estimated using the Global Model of Ambient Particulates (GMAPS) model developed by the World Bank (Cohen *et al.*, 2004).

High concentrations of PM are observed in many parts of the world, with distinct clusters in South-East Asia, South America, and Africa. There is also wide variability in the estimated PM levels by WHO region. WHO Member States are grouped into six geographical regions: AFRO (Africa), AMRO (Americas), EMRO (Eastern Mediterranean), WHO Regional Office for Europe (Europe), SEARO (South-East Asia), and WPRO (Western Pacific). The highest concentrations of PM (population-weighted) occur in parts of the WHO regions of AFRO (Algeria, Angola, Benin, Burkina Faso, Cameroon, Cape Verde, Chad, Comoros, Equatorial Guinea, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Madagascar, Mali, Mauritania, Mauritius, Niger, Nigeria, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Togo), AMRO (Bolivia, Ecuador, Guatemala, Haiti, Nicaragua, Peru), SEARO (Bangladesh, Bhutan, Democratic People's Republic of Korea, India, Indonesia, Maldives, Myanmar, Nepal, Sri Lanka, Thailand, Timor-Leste), and WPRO (Cambodia, China, Cook Islands, Fiji, Kiribati, Lao People's Democratic Republic, Malaysia, Marshall Islands, Federated States of Micronesia, Mongolia, Nauru, Palau, Papua New Guinea, Philippines, Republic of Korea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu, Viet Nam). The six WHO regions are further divided, based on patterns of child and adult mortality, into subregions ranging from A (lowest) to E (highest).

Table 2.1 Number of cities for which data on particulate matter are available from monitoring sites, by WHO subregion and type of particulate matter

Subregion	Number of cities for which data are available		
	PM_{10} or TSP	PM_{10}	TSP
AFR-D	2	0	2
AFR-E	1	0	1
AMR-A	123	118	25
AMR-B	19	12	12
AMR-D	2	2	2
EMR-B	0	0	0
EMR-D	1	1	0
EUR-A	95	56	43
EUR-B	22	7	17
EUR-C	7	1	7
SEAR-B	2	0	2
SEAR-D	11	11	10
WPR-A	5	5	4
WPR-B	14	3	14
World	304	216	139

PM_{10}, particulate matter < 10 µm; TSP, total suspended particles.
WHO Member States in subregions:
AFR-D: Algeria, Angola, Benin, Burkina Faso, Cameroon, Cape Verde, Chad, Comoros, Equatorial Guinea, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Madagascar, Mali, Mauritania, Mauritius, Niger, Nigeria, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Togo;
AFR-E: Botswana, Burundi, Central African Republic, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Eritrea, Ethiopia, Kenya, Lesotho, Malawi, Mozambique, Namibia, Rwanda, South Africa, Swaziland, Uganda, United Republic of Tanzania, Zambia, Zimbabwe;
AMR-A: Canada, Cuba, USA;
AMR-B: Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Brazil, Chile, Colombia, Costa Rica, Dominica, Dominican Republic, El Salvador, Grenada, Guyana, Honduras, Jamaica, Mexico, Panama, Paraguay, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela
AMR-D: Bolivia, Ecuador, Guatemala, Haiti, Nicaragua, Peru;
EMR-B: Bahrain, Cyprus, Islamic Republic of Iran, Jordan, Kuwait, Lebanon, Libyan Arab Jamahiriya, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Tunisia, United Arab Emirates;
EMR-D: Afghanistan, Djibouti, Egypt, Iraq, Morocco, Pakistan, Somalia, Sudan, Yemen;
EUR-A: Andorra, Austria, Belgium, Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Luxembourg, Malta, Monaco, Netherlands, Norway, Portugal, San Marino, Slovenia, Spain, Sweden, Switzerland, United Kingdom;
EUR-B: Albania, Armenia, Azerbaijan, Bosnia and Herzegovina, Bulgaria, Georgia, Kyrgyzstan, Poland, Romania, Slovakia, Tajikistan, The former Yugoslav Republic of Macedonia, Turkey, Turkmenistan, Uzbekistan, Serbia and Montenegro;
EUR-C: Belarus, Estonia, Hungary, Kazakhstan, Latvia, Lithuania, Republic of Moldova, Russian Federation, Ukraine
SEAR-B: Indonesia, Sri Lanka, Thailand;
SEAR-D: Bangladesh, Bhutan, Democratic People's Republic of Korea, India, Maldives, Myanmar, Nepal, Timor-Leste;
WPR-A Australia, Brunei Darussalam, Japan, New Zealand, Singapore;
WPR-B: Cambodia, China, Cook Islands, Fiji, Kiribati, Lao People's Democratic Republic, Malaysia, Marshall Islands, Federated States of Micronesia (Federated States of), Mongolia, Nauru, Niue, Palau, Papua New Guinea, Philippines, Republic of Korea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu, Viet Nam.
Source: Ezzati *et al.* (2004); reproduced with permission from the World Health Organization.

Fig. 2.1 Estimated annual average concentrations of PM_{10} in cities with populations of > 100 000 and in national capitals

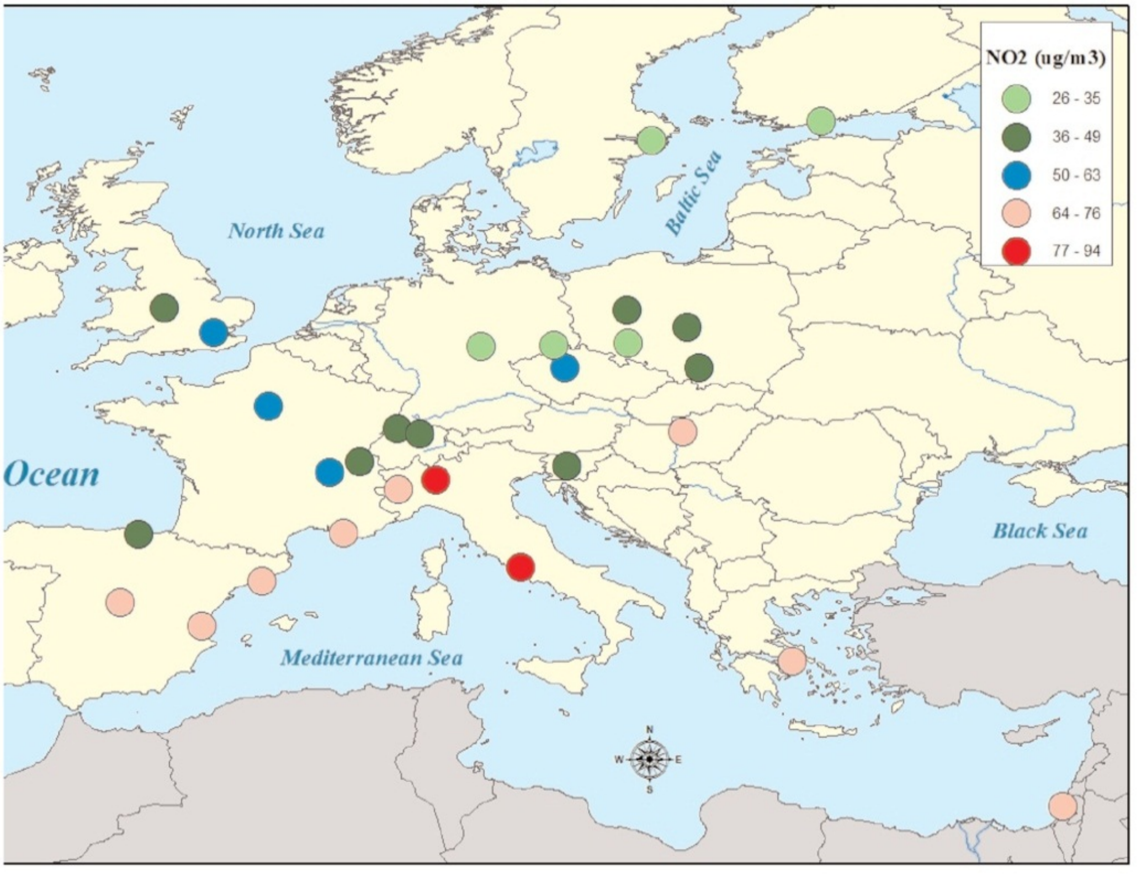
Source: Ezzati *et al.* (2004); reproduced with permission from the World Health Organization.

Table 2.2 Population-weighted predicted PM_{10} and TSP and percentiles of the distribution of estimated concentrations of PM_{10}

Subregion[a]	Predicted point estimate (μg/m³)			Percentiles of the distribution of estimated PM_{10} (mg/m³)				
	PM_{10}	TSP	PM_{10} or TSP	5%	25%	50%	75%	95%
AFR-D	68	195	0.350	32	43	61	72	84
AFR-E	39	104	0.372	30	35	39	44	58
AMR-A	25	39	0.642	24	25	25	25	25
AMR-B	37	79	0.470	35	36	38	39	42
AMR-D	51	146	0.349	37	43	48	53	58
EMR-B	40	118	0.341	23	30	34	39	48
EMR-D	110	276	0.397	62	78	99	110	127
EUR-A	26	49	0.531	25	26	26	27	28
EUR-B	48	118	0.406	41	44	46	48	50
EUR-C	31	90	0.340	21	25	29	33	38
SEAR-B	108	245	0.439	39	86	105	129	151
SEAR-D	84	206	0.409	73	80	84	88	96
WPR-A	32	50	0.646	27	30	32	34	37
WPR-B	89	221	0.403	73	83	89	96	104
World	60	144	0.417	51	56	58	62	65

PM_{10}, particulate matter < 10 μm; TSP, total suspended particles.
[a] For details of WHO subregions, see Table 2.1.
Source: Ezzati *et al.* (2004); reproduced with permission from the World Health Organization.

Fig. 2.2 Geographical distribution of nitrogen dioxide in Europe



Compiled from Katsouyanni *et al.* (2001).

Distribution of pollutants in Europe

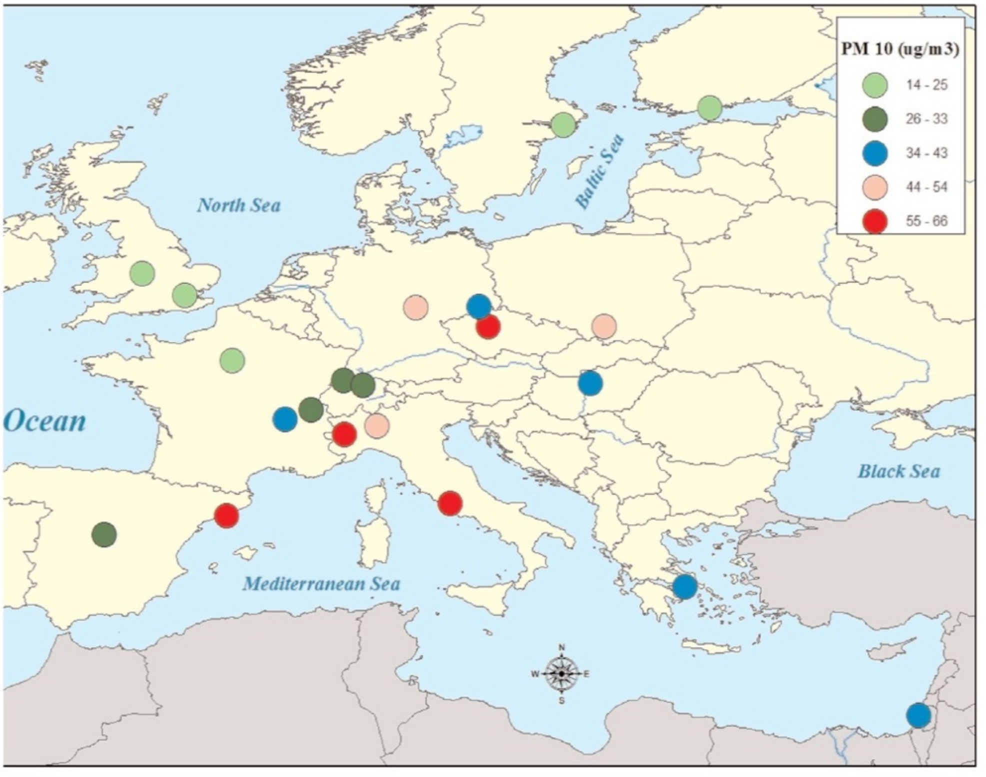
The maps of Europe in Fig. 2.2, Fig. 2.3, Fig. 2.4, Fig. 2.5, and Fig. 2.6 represent distributions of NO_2, PM_{10}, black smoke, SO_2, and ozone in several European cities that are part of the Air Pollution and Health: A European Approach (APHEA) project (Katsouyanni *et al.*, 2001); the corresponding numbers (with concentrations typical for the 1990s) are in Table 2.3.

Substantial variability can be seen in the distribution of the various pollutants. NO_2 has a clear south (high) to north (low) and west (high) to east (low) gradient. The highest concentrations of black smoke and PM_{10} are observed in southern and central eastern Europe. The highest concentrations of SO_2 are in the east, followed by those in the south. The pattern for ozone is not so clear, mostly because of the placement of the monitors in each city. Some high concentrations can be seen in southern Europe, however, due to primary emissions and the climate, and in the north, mainly due to long-range transport. More information on the geographical distribution and composition of PM in Europe is given in Putaud *et al.* (2004) and Van Dingenen *et al.* (2004).

Distribution of pollutants in the USA

Fig. 2.7, Fig. 2.8, and Fig. 2.9 show the distribution of $PM_{2.5}$ in the USA (Bell *et al.*, 2007). Concentrations of $PM_{2.5}$ are high in the Midwest

Fig. 2.3 Geographical distribution of PM_{10} in Europe



Compiled from Katsouyanni *et al.* (2001).

and eastern USA, as well as in southern California. However, as we can see from Fig. 2.8 and Fig. 2.9, the geographical distribution varies by season. The highest concentrations are observed in the east and Midwest in the summer, but in the Southwest in the winter.

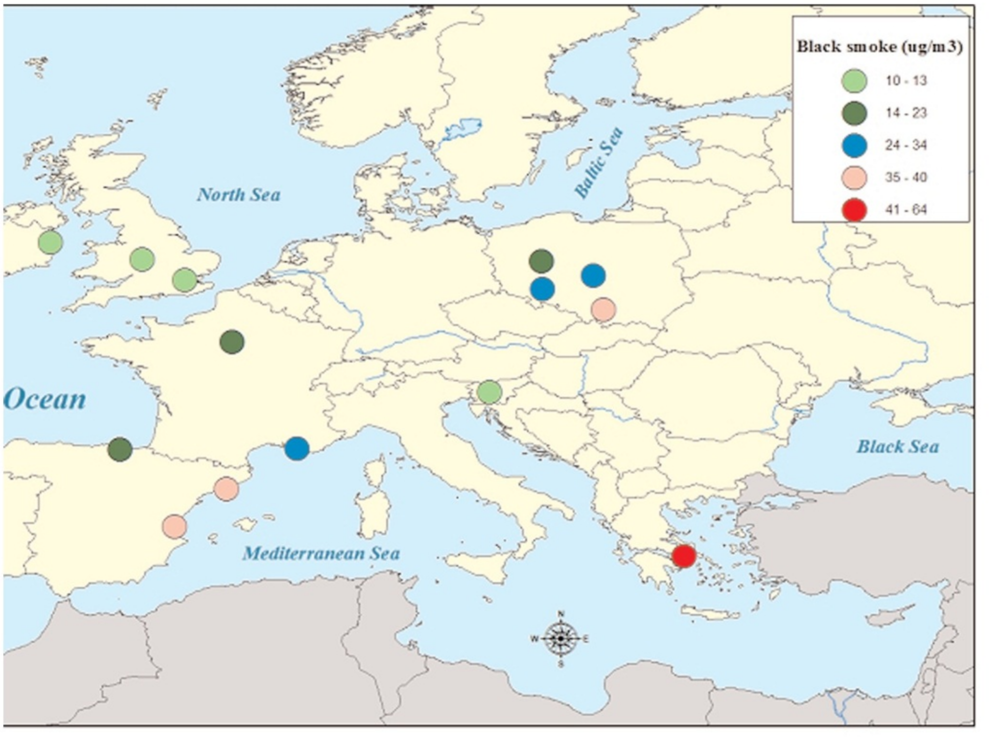
Is there evidence that the health effects of mixes of pollutants display geographical variation?

In the first phase of the APHEA project, geographical variations in the estimated (short-term) effects of pollutants (PM, SO_2) were observed, with smaller estimates in central eastern European cities and larger estimates in southern and north-western European cities (Katsouyanni *et al.*, 1997). Subsequently, a systematic effort was made within APHEA to identify potential effect modifiers among the variables that characterize the air pollution mix, climate, health status of the population, and geographical areas (Katsouyanni *et al.*, 2001).

Table 2.4 and Table 2.5 give the effect modification identified in the APHEA project. In cities with higher long-term NO_2 levels, the estimated effects of PM_{10} were greater; similar effects were seen in cities with higher average temperatures and in those with a larger proportion of elderly persons. The distribution of these effect modifiers explains, to a certain extent, the geographical differences seen in Table 2.5 and is supported by other studies, such as the meta-analysis by Levy *et al.* (2000).

In the National Mortality, Morbidity and Air Pollution Study (NMMAPS), geographical

Fig. 2.4 Geographical distribution of black smoke in Europe



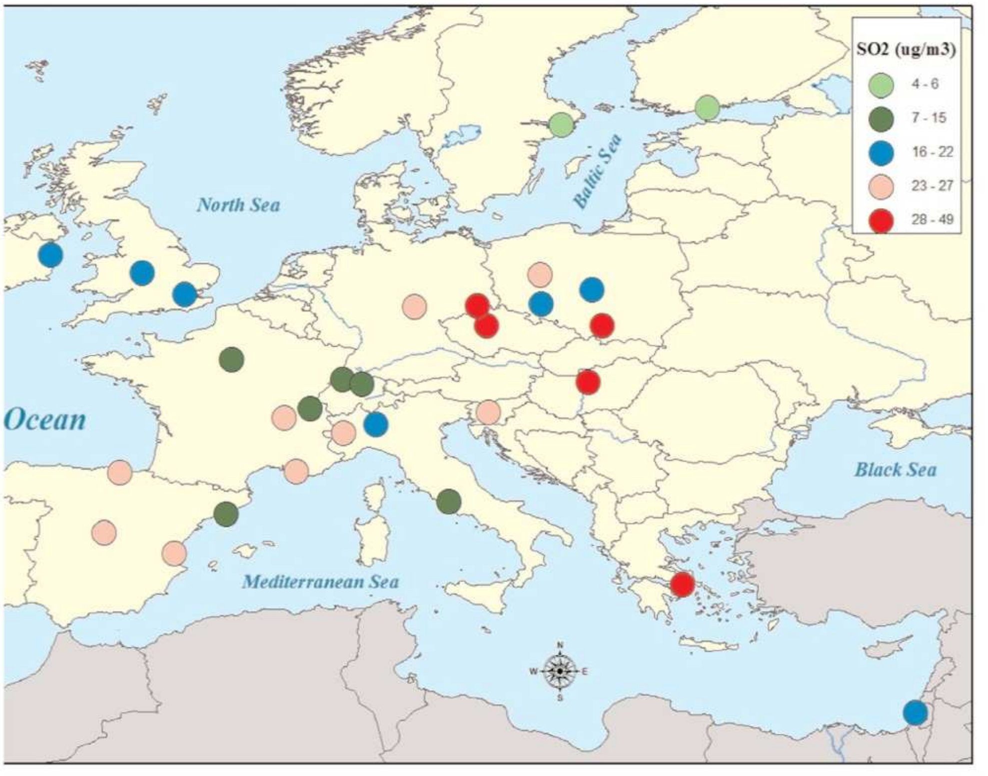
Compiled from Katsouyanni *et al.* (2001).

differences in PM_{10} estimates were also observed, with higher estimates in the north-eastern region of the USA (Samet *et al.*, 1999).

Conclusion and points of discussion

- There is wide geographical variability in concentrations of air pollutants.
- The geographical distribution varies by season.
- Information available today is limited, especially for specific constituents of the air pollution mix that may be of particular interest when the objective of the study is cancer. Those constituents are generally not measured routinely.
- More information is available from parts of the world where the concentrations of pollutants are, in fact, not so high, and less information is available where the exposure is more severe.
- However, in proportional terms, the health effects of exposure to air pollution may be more important in areas of the world where the exposure is not highest, due to interaction with other characteristics of the environment and/or the populations.
- There is evidence from studies of the short-term exposure to air pollution that several variables modify the effects of air pollutants, and some of them are probably related to characteristics of the air pollution mix.

Fig. 2.5 Geographical distribution of sulfur dioxide in Europe



Compiled from Katsouyanni *et al.* (2001).

Addendum (2012 update) [1]

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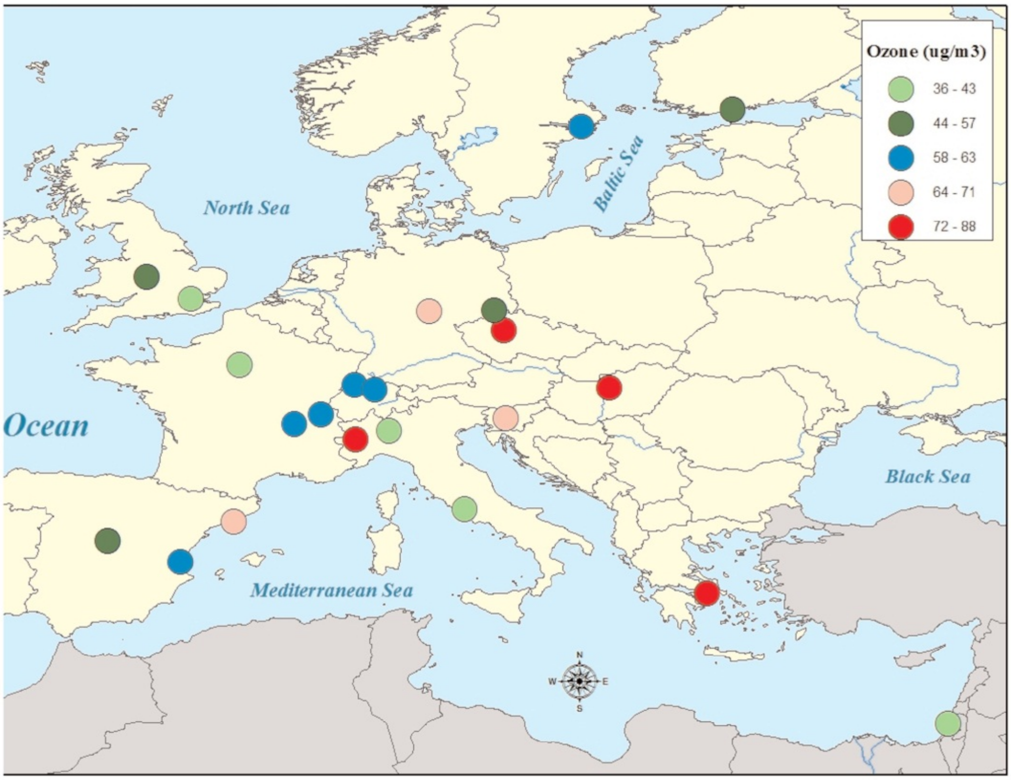
In general, the conclusions of the 2004 version of this chapter still hold true. However, our understanding of the role of geographical variability of pollutants on human exposure and health effects has advanced. Also, much progress has been made on the methodological study of geographical variation of air pollution, which can be applied to two distinct areas: geographical variation across large areas or continents, and geographical variation within a city or a relatively limited area.

Geographical variation across large areas or continents

In the WHO Air Quality Guidelines: Global update, 2006, a comprehensive chapter covers data from measurements of monitored air pollutant levels worldwide (Sivertsen, 2006). The pollutants covered are mainly PM, NO_2, SO_2, and ozone. The highest concentrations of PM_{10} and SO_2 are in Africa, South-East Asia, and Latin America. However, ozone and NO_2, although highest in Latin America, may be found at very high levels everywhere in the world (including Europe and the USA). Trends show a decline in most areas; however, there is concern that in

[1] See Preface for explanation of updating process.

Fig. 2.6 Geographical distribution of ozone in Europe



Compiled from Katsouyanni *et al.* (2001).

developing countries and fast-developing cities the situation may deteriorate due to an increase of vehicle traffic, particularly with vehicles that are old and poorly maintained. The data available on $PM_{2.5}$ are still limited, and data on other PM fractions (such as ultrafine particles) and chemical constituents are very sparse. In addition, measurements are not easily comparable due to the techniques used and the varying characteristics of places where monitors are located. All pollutants except ozone have higher concentrations in urban areas (and within urban areas, near heavy traffic roads).

A recent report by the European Environmental Agency (EEA, 2012) indicates that the most problematic pollutants in Europe are PM and ozone. Levels are determined mostly by emissions within Europe, but also, to a lesser extent, from intercontinental transport. Several pollutants are considered, including benzo[*a*]pyrene (B[*a*]P), lead, and benzene (C_6H_6). It is reported that 90–95% of the urban population in Europe is exposed to levels of $PM_{2.5}$ above the WHO air quality guidelines (AQG), 80–81% to corresponding levels of PM_{10}, > 97% to higher levels of ozone, and 93–94% to levels of B[*a*]P above the WHO guideline. PM exceedances largely occur in central, eastern, and southern Europe, but levels are decreasing. Ozone levels exceed the AQG mainly in southern Europe, and no apparent decreases are observed. There are problems with NO_2 levels everywhere in Europe, especially in urban areas, and an uncertain decreasing trend. SO_2 appears to be problematic in a few countries (the Balkans and Turkey). The EEA report attempted to cover additional pollutants, such as metals and B[*a*]P, and underlined the lack of monitoring data, with some countries

Table 2.3 Air pollutant concentrations in several European cities participating in the APHEA2 Project

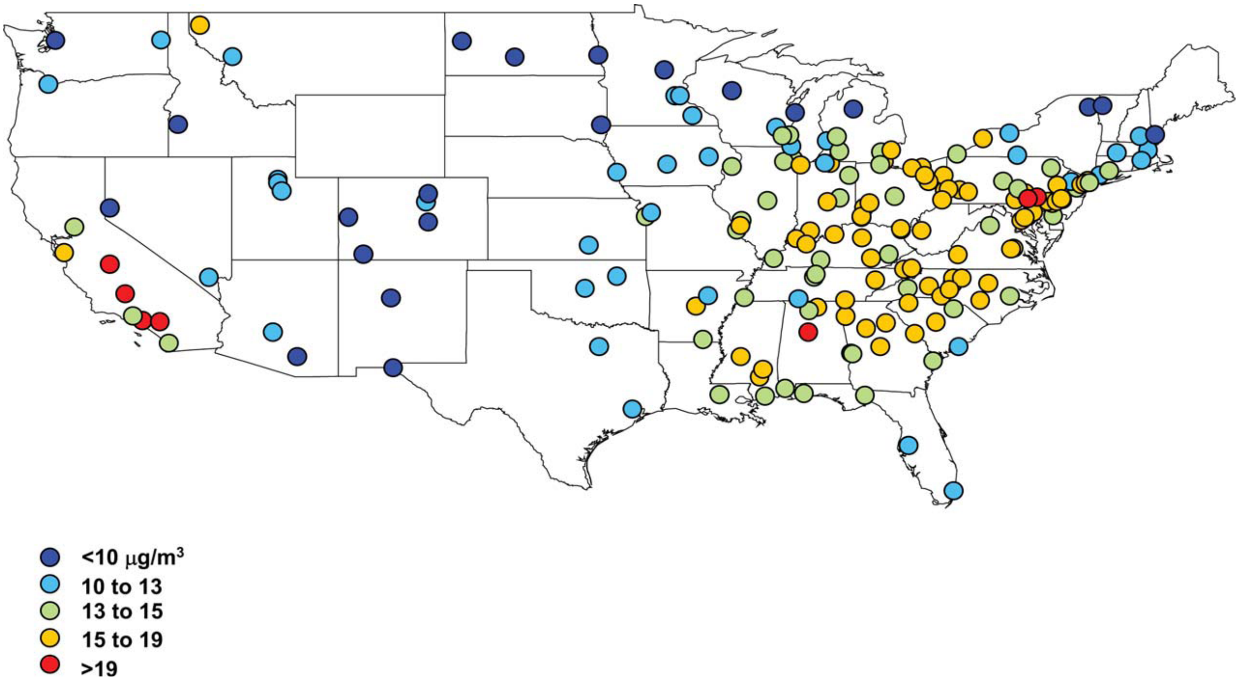
City	Study period	Population (× 1000)	Concentration (μg/m³)				
			PM_{10} (24 h)	Black smoke (24 h)	Sulfur dioxide	Ozone	Nitrogen dioxide (24 h)
Athens	1/92–12/96	3073	40	64	46	83	74
Barcelona	1/91–12/96	1644	60	39	12	71	69
Basel	1/90–12/95	360	28		9	62	38
Bilbao	4/92–3/96	667		23	23		49
Birmingham	1/92–12/96	2300	21	11	19	56	46
Budapest	1/92–12/95	1931	40[a]		39	82	76
Cracow	1/90–12/96	746	54[a]	36	49		44
Dublin	1/90–12/96	482		10	21		
Erfurt	1/91–12/95	216	48		26	71	35
Geneva	1/90–12/95	317	33a		9	63	45
Helsinki	1/93–12/96	828	23a		6	57	33
Ljubljana	1/92–12/96	322		13	27	71	46
Lodz	1/90–12/96	828		30	19		39
London	1/92–12/96	6905	25	11	22	43	61
Lyon	1/93–12/97	416	39		23	61	63
Madrid	1/92–12/95	3012	33		26	52	70
Marseille	1/90–12/95	855		34	23		71
Milano	1/90–12/96	1343	47[a]		20	38	94
Paris	1/91–12/96	6700	22	21	15	38	53
Poznan	1/90–12/96	582		23	23		47
Prague	2/92–12/96	1213	66		36	78	58
Rome	1/92–12/96	2775	57[a]		11	41	88
Stockholm	1/90–12/96	1126	14		4	63	26
Tel Aviv	1/91–12/96	1141	43		19	36	70
Teplice	1/90–12/97	625	42		46	52	32
Torino	1/90–12/96	926	65[a]		23	88	76
Valencia	1/94–12/96	753		40	25	59	66
Wroclaw	1/90–12/96	643		33	21		27
Zurich	1/90–12/95	540	28[a]		10	62	40

PM_{10}, particulate matter < 10 μm.

[a] PM_{10} was estimated using a regression model relating collocated PM_{10} measurements to the black smoke or total suspended particles.

Source: Katsouyanni *et al.* (2001); adapted with permission from Lippincott Williams and Wilkins/Wolters Kluwer Health.

Fig. 2.7 $PM_{2.5}$ averages (μg/m³) for 187 counties in the USA, 2000–2005



Source: Bell *et al.* (2007).

not contributing data at all. From the available data, it appears that the problem with exceedances in heavy metal concentrations is mainly local and associated with industrial sources. B[*a*]P exposure is mainly problematic in central eastern Europe, but the overall emissions are increasing in the whole continent as well.

It is worth noting that in the WHO Report on Global Health Risks (WHO, 2009), urban outdoor air pollution was included in the 19 leading risk factors for mortality, with greatest effects in middle-income countries.

The lack of adequate monitoring data on the various air pollutants of interest, which is mentioned in all the reports, leads to attempts to develop modelling methods that take advantage of the availability of remote sensing data and the possibility to combine these with

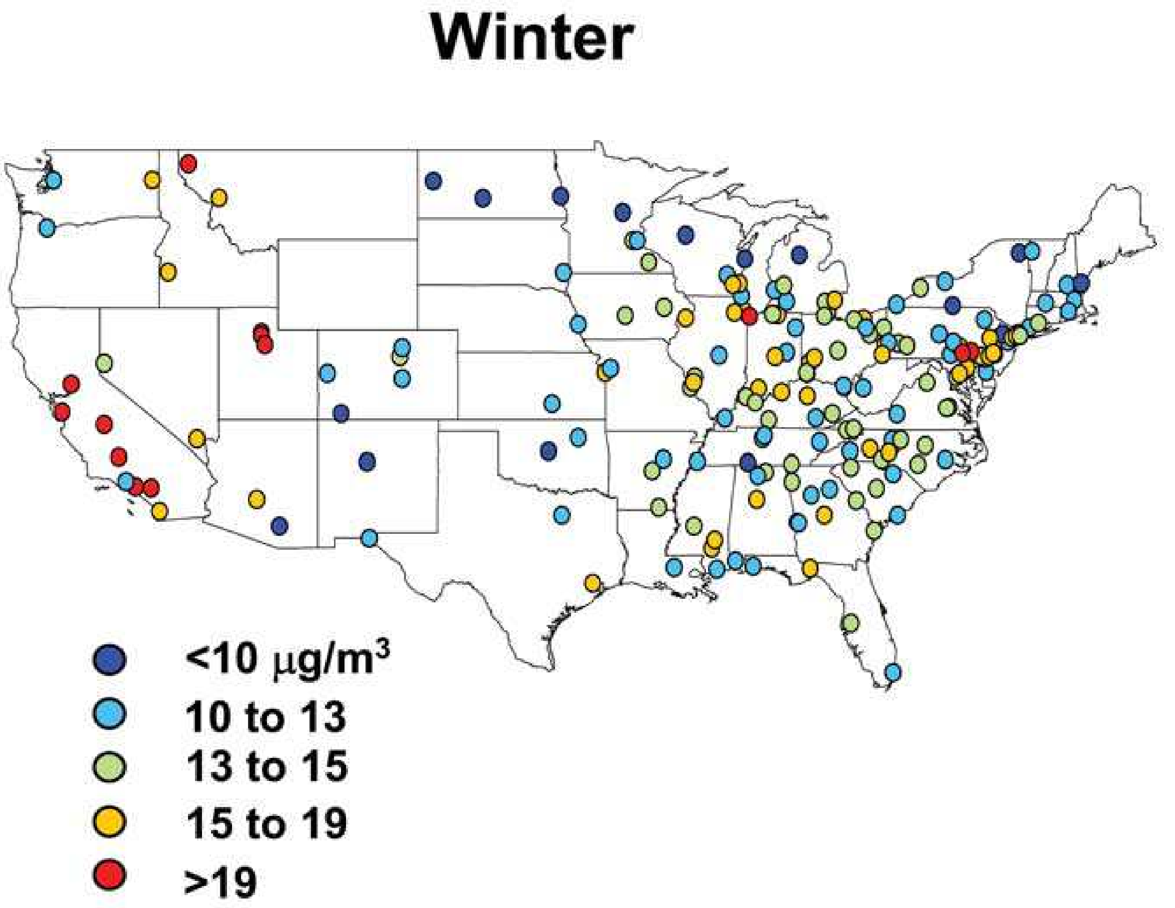
Table 2.4 Percentage increase in the daily number of deaths associated with an increase of 10 μg/m³ in PM_{10} concentrations, by levels of important effect modifiers

Effect modifier	Increase in daily number of deaths (%)	
	Low level[a]	High level[a]
Average long-term nitrogen dioxide	0.19	0.80
Average annual temperature	0.28	0.82
Proportion of population aged > 65 years	0.54	0.76

[a] Low level of effect modifier is defined as the 25th percentile and high level as the 75th percentile of the corresponding distribution of effect modifier across cities. The actual levels were 40 mg/m³ and 70 mg/m³ for nitrogen dioxide, 9 °C and 14 °C for temperature, and 13% and 16% for the proportion of persons aged > 65 years.

Source: Katsouyanni *et al.* (2001); adapted with permission from Lippincott Williams and Wilkins/Wolters Kluwer Health.

Fig. 2.8 Seasonal $PM_{2.5}$ averages (µg/m³) for 187 counties in the USA, 2000–2005



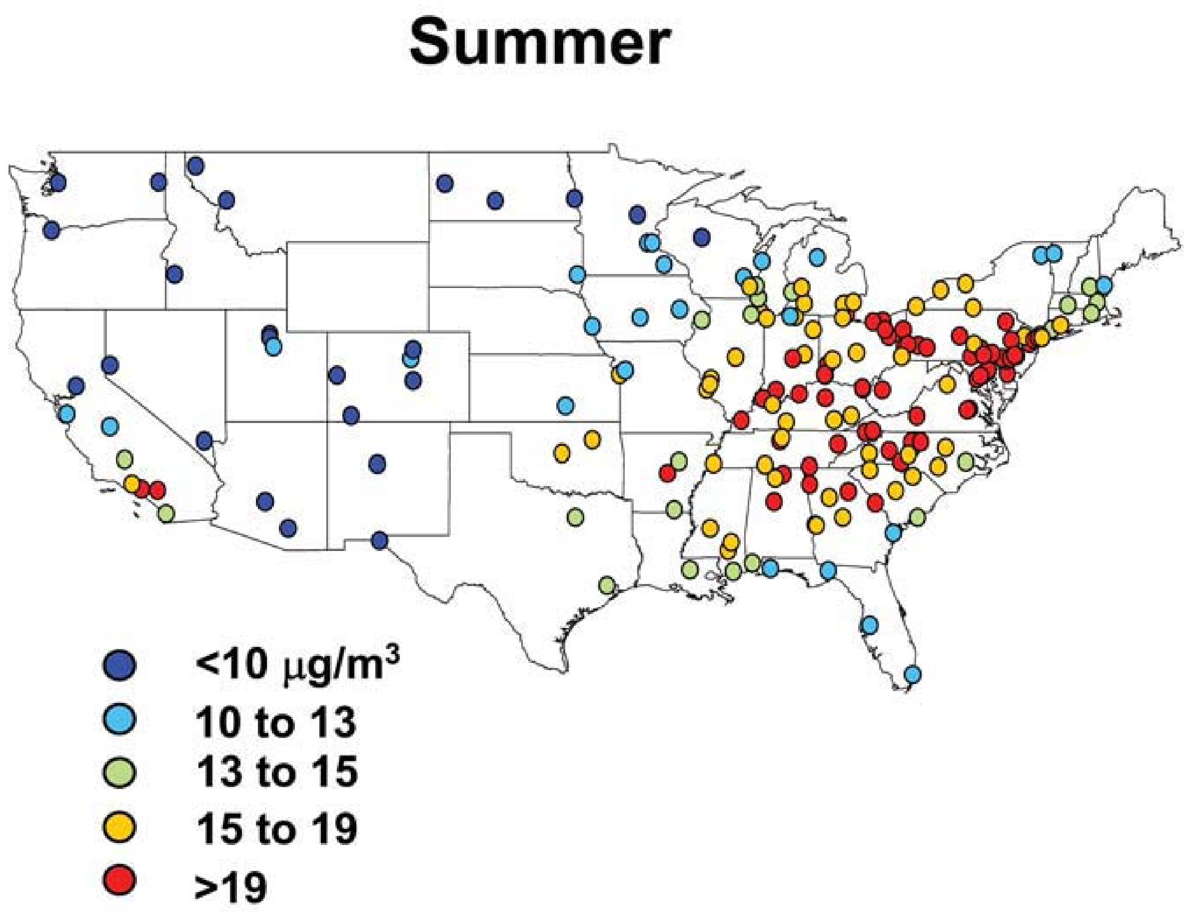
Source: Bell *et al.* (2007).

chemical-transport models and measurements (where available). Thus, Brauer *et al.* (2012) generated global estimates for $PM_{2.5}$ and ozone and were able to estimate that a large percentage of the world's population lives in areas with levels of $PM_{2.5}$ exceeding the WHO AQG targets, mainly in South-East Asia, while seasonal ozone levels are exceeded in all continents. They predicted an increasing trend in the global population-weighted exposure to $PM_{2.5}$ and a small decreasing trend for the same exposure to ozone. Evans *et al.* (2012) estimated the global adult mortality attributable to anthropogenic $PM_{2.5}$ exposure based on remote sensing data. Similar combinations of data and methods can be applied to large analytical epidemiological studies to estimate the retrospective exposure to air pollutants, as has been done, for example, by Hystad *et al.* (2012) in a case–control study in Canada.

Geographical variation within a city or a relatively limited area

In epidemiological studies where both the within-city and the between-cities spatial contrasts could be taken into account, it has been shown that studying the within-city contrast led

Fig. 2.9 Seasonal $PM_{2.5}$ averages (μg/m³) for 187 counties in the USA, 2000–2005



Source: Bell *et al.* (2007).

to higher relative risk estimates (Miller *et al.*, 2007; Jerrett *et al.*, 2005; Krewski *et al.*, 2009). Thus, efforts to model the geographical variability within cities and then estimate individualized exposure were shown to be very important for the study of air pollution health effects. To achieve this, land-use regression (LUR) models have been developed and applied in the USA and Europe. LUR models are statistical models (in contrast to dispersion models) that link various geographical information system (GIS)-based spatial characteristics (covariates) with fixed site measurements in a relatively homogeneous area. The models can be used either to predict long-term (e.g. annual) averages or to attempt to estimate spatiotemporal variations (e.g. predict daily concentrations). In the former case, the covariates included (in addition to a smooth function of latitude and longitude) may be traffic burden (typically in a buffer around a point in space), the existence of a point source, population density, and green space, for example, whereas in the latter case additional covariates characterizing the weather (e.g. daily temperature) or temporal trends (e.g. day of the week) are included. More details may be found in Jerrett *et al.* (2005b), Ryan and LeMasters (2007), and Hoek *et al.* (2008).

Table 2.5 Percentage increase in the daily number of deaths associated with an increase of 10 µg/m³ in PM_{10} concentrations, by geographical area

Geographical area	Southern Europe	North-western Europe	Central eastern Europe
Increase in the daily number of deaths (%)	0.87	0.73	0.22

PM_{10}, particulate matter < 10 µm.
Source: Katsouyanni *et al.* (2001); adapted with permission from Lippincott Williams and Wilkins/Wolters Kluwer Health.

In the USA, such models have been applied in the American Cancer Society's Cancer Prevention 2 study (Krewski *et al.*, 2009). The refined spatial estimates resulted in larger estimates of the effects of air pollution. In a study in Boston, Maynard *et al.* (2007) modelled daily concentrations of black carbon and sulfates and investigated their short-term association with cardiovascular and respiratory mortality. They found very significant associations with black carbon, in spite of the larger errors that are inherent in daily predictions.

Recently in Europe, a large-scale effort has been undertaken within the EC-funded multicity project ESCAPE. LUR models have been built in 20 European areas across the continent for several PM indicators, including PM_{10}, $PM_{2.5}$, coarse PM, and $PM_{2.5}$ absorbance, and in 36 areas for NO_2 and nitrogen oxides (NO_x) (Eeftens *et al.*, 2012; Cyrys *et al.*, 2012). The modelling strategy allowed for local differentiation. With this application it was shown that models with good predictive ability can be developed in many areas and it became possible to compare within-city and between-city geographical contrasts. Better models are built for PM indicators related to the covariates included in the model (i.e. PM absorbance since traffic sources are specifically reflected in the model by traffic load). This effort showed once more that in Europe pollution concentrations display a gradient from north (cleaner) to south (more polluted).

Through the use of LUR models, and possibly other types of validated models, long-term effects of air pollution can be further studied, taking into account a more personalized exposure estimate for subjects participating in cohort studies. Most studies have taken the residential address as input for this individual estimate. Through the use of technology, additional data may be collected on the average trajectory of an individual (including work address and commuting patterns) (Almanza *et al.*, 2012). In this way, the important within-city contrasts in exposure will be taken into account and yield much better effect estimates. Further improvements can be achieved by bringing in the temporal dimension (Maynard *et al.*, 2007) and estimating short-term effects as well.

References

Almanza E, Jerrett M, Dunton G *et al.* (2012). A study of community design, greenness, and physical activity in children using satellite, GPS and accelerometer data. *Health Place*, 18: 46–54. doi:10.1016/j.healthplace.2011.09.003 PMID:22243906

Bell ML, Dominici F, Ebisu K *et al.* (2007). Spatial and temporal variation in PM(2.5) chemical composition in the United States for health effects studies. *Environ Health Perspect*, 115: 989–995. doi:10.1289/ehp.9621 PMID:17637911

Brauer M, Amann M, Burnett RT *et al.* (2012). Exposure assessment for estimation of the global burden of disease attributable to outdoor air pollution. *Environ Sci Technol*, 46: 652–660. doi:10.1021/es2025752 PMID:22148428

Cohen AJ, Anderson HR, Ostro B *et al.* (2004). Urban air pollution. In: Ezzati M, Lopez D, Rodgers A, Murray CJL, eds. *Comparative Quantification of Health Risks: Global and Regional Burden of Disease due to Selected Major Risk Factors*, Vol. 2. Geneva: World Health Organization, pp. 1353–1434.

Cyrys J, Eeftens M, Heinrich J *et al.* (2012). Variation of NO_2 and NO_x concentration between and within 36 European study areas: Results from the ESCAPE

study. *Atmos Environ*, 62: 374–390. doi:10.1016/j.atmosenv.2012.07.080
EEA (2012). *Air Quality in Europe - 2012 Report*, Copenhagen: European Environmental Agency.
Eeftens M, Beelen R, de Hoogh K *et al.* (2012). Development of Land Use Regression models for PM(2.5), PM(2.5) absorbance, PM(10) and PM(coarse) in 20 European study areas; results of the ESCAPE project. *Environ Sci Technol*, 46: 11195–11205. doi:10.1021/es301948k PMID:22963366
Evans J, van Donkelaar A, Martin RV *et al.* (2012). Estimates of global mortality attributable to particulate air pollution using satellite imagery. *Environ Res*, 120: 33–42. doi:10.1016/j.envres.2012.08.005 PMID:22959329
Ezzati M, Lopez AD, Rodgers A, Murray CJL (2004). *Comparative Quantification of Health Risks: Global and Regional Burden of Disease due to Selected Major Risk Factors*, Vol. 2. Geneva: World Health Organization. Available at http://whqlibdoc.who.int/publications/2004/9241580348_eng_Volume2.pdf
Hoek G, Beelen R, de Hoogh K *et al.* (2008). A review of land –use regression models to assess spatial variation of outdoor air pollution. *Atmos Environ*, 42: 7561–7578. doi:10.1016/j.atmosenv.2008.05.057
Hystad P, Demers PA, Johnson KC *et al.* (2012). Spatiotemporal air pollution exposure assessment for a Canadian population-based lung cancer case-control study. *Environ Health*, 11: 22 doi:10.1186/1476-069X-11-22 PMID:22475580
Jerrett M, Arain A, Kanaroglou P *et al.* (2005b). A review and evaluation of intraurban air pollution exposure models. *J Expo Anal Environ Epidemiol*, 15: 185–204. doi:10.1038/sj.jea.7500388 PMID:15292906
Jerrett M, Burnett RT, Ma R *et al.* (2005). Spatial analysis of air pollution and mortality in Los Angeles. *Epidemiology*, 16: 727–736. doi:10.1097/01.ede.0000181630.15826.7d PMID:16222161
Katsouyanni K, Touloumi G, Samoli E *et al.* (2001). Confounding and effect modification in the short-term effects of ambient particles on total mortality: results from 29 European cities within the APHEA2 project. *Epidemiology*, 12: 521–531. doi:10.1097/00001648-200109000-00011 PMID:11505171
Katsouyanni K, Touloumi G, Spix C *et al.* (1997). Short-term effects of ambient sulphur dioxide and particulate matter on mortality in 12 European cities: results from time series data from the APHEA project. Air Pollution and Health: a European Approach. *BMJ*, 314: 1658–1663. doi:10.1136/bmj.314.7095.1658 PMID:9180068
Krewski D, Jerrett M, Burnett RT *et al.* (2009). Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality. *Res Rep Health Eff Inst*, 140: 5–114, discussion 115–136. PMID:19627030
Levy JI, Hammitt JK, Spengler JD (2000). Estimating the mortality impacts of particulate matter: what can be learned from between-study variability? *Environ Health Perspect*, 108: 109–117. doi:10.1289/ehp.00108109 PMID:10656850
Maynard D, Coull BA, Gryparis A, Schwartz J (2007). Mortality risk associated with short-term exposure to traffic particles and sulfates. *Environ Health Perspect*, 115: 751–755. doi:10.1289/ehp.9537 PMID:17520063
Miller KA, Siscovick DS, Sheppard L *et al.* (2007). Long-term exposure to air pollution and incidence of cardiovascular events in women. *N Engl J Med*, 356: 447–458. doi:10.1056/NEJMoa054409 PMID:17267905
Putaud J, Raes FP, Van Dingenen RM *et al.* (2004). A European aerosol phenomenology. Part 2: Chemical characteristics of particulate matter at kerbside, urban, rural and background sites in Europe. *Atmos Environ*, 38: 2579–2595. doi:10.1016/j.atmosenv.2004.01.041
Ryan PH & LeMasters GK (2007). A review of land-use regression models for characterizing intraurban air pollution exposure. *Inhal Toxicol*, 19: Suppl 1: 127–133. doi:10.1080/08958370701495998 PMID:17886060
Samet J, Zeger S, Dominici F *et al.* (1999). *The National Mortality, Morbidity and Air Pollution Study (NMMAPS). Final Report*. Boston, MA: Health Effects Institute (www.healtheffects.org)
Sivertsen B (2006). Global ambient air pollution concentrations, trends. In: *Air Quality Guidelines, Global Update 2005*. Copenhagen: WHO Regional Office for Europe, pp. 31–59.
Van Dingenen RM, Raes FPE, Putaud J *et al.* (2004). A European aerosol phenomenology. Part 1: Physical characteristics of particulate matter at kerbside, urban, rural and background sites in Europe. *Atmos Environ*, 38: 2561–2577. doi:10.1016/j.atmosenv.2004.01.040
WHO (2003). *Health Aspects of Air Pollution with Particulate Matter, Ozone and Nitrogen Dioxide. Report on a WHO Working Group*. EUR/03/5042688. Copenhagen: WHO Regional Office for Europe. Available at www.euro.who.int/document/e79097.pdf
WHO (2009). *Global Health Risks:* Mortality and Burden of Disease Attributable to Selected Major Risk Factors. Geneva: World Health Organization.