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Air quality in Europe — 2018 report

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Executive summary

The current report presents an updated overview and analysis of air quality in Europe from 2000 to 2016. It reviews the progress made towards meeting the air quality standards established in the two EU Ambient Air Quality Directives and towards the World Health Organization (WHO) air quality guidelines (AQGs). It also presents the latest findings and estimates on population and ecosystem exposure to the air pollutants with the greatest impacts and effects. The evaluation of the status of air quality is based mainly on reported ambient air measurements, in conjunction with modelling data and data on anthropogenic emissions and their evolution over time.

For the first time, the *Air quality in Europe* report presents information on concentrations for most air pollutants at country level for all of the EEA-39 countries (the 33 member countries and six cooperating countries; see Box ES.1). This is thanks to an improvement in the official reporting of data by all countries. We would like to recognise and acknowledge the support from the air quality experts in the different countries.

Europe's air quality

Particulate matter

Concentrations of particulate matter (PM) continued to exceed the EU limit values and the WHO AQGs in large parts of Europe in 2016. For PM with a diameter of 10 µm or less (PM_{10}), concentrations above the EU daily limit value were registered at 19 % of the reporting stations in 19 of the 28 EU Member States (EU-28) and in eight other reporting countries; for $PM_{2.5}$, concentrations above the annual limit value were registered at 5 % of the reporting stations in four Member States and four other reporting countries.

The long-term WHO AQG for PM_{10} was exceeded at 48 % of the stations and in all the reporting countries except Estonia, Iceland, Ireland and Switzerland. The long-term WHO AQG for $PM_{2.5}$ was exceeded at 68 % of the stations located in all the reporting countries except Estonia, Finland, Hungary, Norway and Switzerland.

Box ES.1 New in the Air quality in Europe — 2018 report

The Air quality in Europe report series from the EEA presents regular assessments of Europe's air pollutant emissions and concentrations, and their associated impacts on health and the environment.

Based upon the latest official data available from countries, this updated 2018 report presents new information, including:

- updated data on air pollutant emissions and concentrations, and urban population exposure (for 2016);
- extended country scope in the analysis of concentrations, with a more detailed analysis for all the reporting countries;
- information on the status of reporting of $PM_{2.5}$ (particulate matter with a diameter of 2.5 µm or less) speciation, ozone precursors, and polycyclic aromatic hydrocarbons;
- updated assessments of total population and ecosystems exposure data, and air quality impacts on health (for 2015);
- evolution over time of the health impacts of air pollution;
- a special focus on ozone, with a summary of ozone formation mechanisms in the atmosphere, as well as some abatement strategies and past trends in Europe.

A total of 13 % of the EU-28 urban population was exposed to PM_{10} levels above the daily limit value and approximately 42 % was exposed to concentrations exceeding the stricter WHO AQG value for PM_{10} in 2016. Regarding $PM_{2.5}$, 6 % of the urban population in the EU-28 was exposed to levels above the EU limit value, and approximately 74 % was exposed to concentrations exceeding the WHO AQG value for $PM_{2.5}$ in 2016 (Table ES.1). The percentage of the EU-28 urban population exposed to PM_{10} and $PM_{2.5}$ levels above limit values and WHO guidelines in 2016 was the lowest since 2000 (2006 for $PM_{2.5}$), showing a decreasing trend.

However, four Member States had yet to meet the exposure concentration obligation.

Ozone

In 2016, 17 % of stations registered concentrations above the EU ozone (O_3) target value for the protection of human health. The percentage of stations measuring concentrations above this target value was considerably smaller than in 2015 (41 %) but higher than in 2014, reflecting the interannual variability of O_3 concentrations. These stations were located in 14 of the EU-28 and five other reporting European countries. The long-term objective was met in only 17 % of stations in 2016. The WHO AQG value for O_3 was exceeded in 96 % of all the reporting stations, the same percentage as in 2015.

About 12 % of the EU-28 urban population was exposed to O_3 concentrations above the EU target value threshold, which is a considerable decrease compared with the high exposure of 2015 (30 %). However, the percentage is still higher than the 7 % recorded in 2014. The percentage of the EU-28 urban population exposed to O_3 levels exceeding the WHO AQG value was 98% in 2016, scarcely showing any fluctuation since 2000 (Table ES.1).

Nitrogen dioxide

The annual limit value for nitrogen dioxide (NO_2) continues to be widely exceeded across Europe, even if concentration and exposure are decreasing. In 2016, around 12 % of all the reporting stations recorded concentrations above this standard, which is the same as the WHO AQG. These stations were located in 19 of the EU-28 and four other reporting countries, and 88 % of concentrations above this limit value were observed at traffic stations.

Table ES.1 Percentage of the urban population in the EU-28 exposed to air pollutant concentrations above certain EU and WHO reference concentrations (minimum and maximum observed between 2014 and 2016)

Pollutant	EU reference value (a)	Exposure estimate (%)	WHO AQG (a)	Exposure estimate (%)
$PM_{2.5}$	Year (25)	6-8	Year (10)	74-85
PM_{10}	Day (50)	13-19	Year (20)	42-52
O_3	8-hour (120)	7-30	8-hour (100)	95-98
NO_2	Year (40)	7-8	Year (40)	7-8
BaP	Year (1)	20-24	Year (0.12) RL	85-90
SO_2	Day (125)	< 1	Day (20)	21-38

Key: < 5 % | 5-50 % | 50-75 % | > 75 %

Notes: (a) In µg/m³; except BaP, in ng/m³.

The reference concentrations include EU limit or target values, WHO air quality guidelines (AQGs) and an estimated reference level (RL). For some pollutants, EU legislation allows a limited number of exceedances. This aspect is considered in the compilation of exposure in relation to EU air quality limit and target values.

The comparison is made for the most stringent EU limit value set for the protection of human health. For PM_{10}, the most stringent limit value is for the 24-hour mean concentration, and for NO_2 it is the annual mean limit value.

The estimated exposure range refers to the maximum and minimum values observed in a recent 3-year period (2014-2016) and includes variations attributable to meteorology (as dispersion and atmospheric conditions differ from year to year), and to the number of available data series (monitoring stations and/or selected cities) that will influence the total number of the monitored population.

As the WHO has not set AQGs for BaP, the reference level in the table was estimated assuming WHO unit risk for lung cancer for polycyclic aromatic hydrocarbon mixtures and an acceptable risk of additional lifetime cancer risk of approximately 1 in 100 000.

Source: EEA, 2018f.

Seven per cent of the EU-28 urban population lived in areas with concentrations above the annual EU limit value and the WHO AQG for NO_2 in 2016 (Table ES.1), which represents the lowest value since 2000.

Benzo[a]pyrene, an indicator for polycyclic aromatic hydrocarbons

Thirty-one per cent of the reported benzo[*a*]pyrene (BaP) measurement stations reported concentrations above 1.0 ng/m^3 in 2016. They belonged to 13 Member States (out of 25 EU-28 and two other countries reporting data) and were located mostly in urban areas. Twenty-one per cent of the EU-28 urban population was exposed to BaP annual mean concentrations above the EU target value in 2016 and about 90 % to concentrations above the estimated reference level (Table ES.1).

Other pollutants: sulphur dioxide, carbon monoxide, benzene and toxic metals

Only 23 stations (out of 1 600) in five reporting countries reported values for sulphur dioxide (SO_2) above the EU daily limit value in 2016. However, 37 % of all SO_2 stations, located in 30 reporting countries measured SO_2 concentrations above the WHO AQG. This signified that 23 % of the EU-28 urban population in 2016 was exposed to SO_2 levels exceeding the WHO AQG.

Exposure of the European population to carbon monoxide (CO) concentrations above the EU limit value and WHO AQG is very localised and infrequent. Only five stations (of which four were outside the EU-28) registered concentrations above the EU limit value in 2016.

Likewise, concentrations above the limit value for benzene (C_6H_6) were observed at only four European stations (all of them located in the EU-28) in 2016.

Concentrations of arsenic (As), cadmium (Cd), lead (Pb) and nickel (Ni) in the air are generally low in Europe, with few exceedances of the environmental standards. However, these pollutants contribute to the deposition and accumulation of toxic metal levels in soils, sediments and organisms.

Impacts of air pollution on health

Air pollution continues to have significant impacts on the health of the European population, particularly in urban areas. It also has considerable economic impacts, cutting lives short, increasing medical costs and reducing productivity through working days lost across the economy. Europe's most serious pollutants in terms of harm to human health, are PM, NO_2 and ground-level O_3.

Estimates of the health impacts attributable to exposure to air pollution indicate that $PM_{2.5}$ concentrations in 2015 ([1]) were responsible for about 422 000 premature deaths originating from long-term exposure in Europe (over 41 countries; see Table 10.1), of which around 391 000 were in the EU-28. The estimated impacts on the population in these 41 European countries of exposure to NO_2 and O_3 concentrations in 2015 were around 79 000 and 17 700 premature deaths per year, respectively, and in the EU-28 around 76 000 and 16 400 premature deaths per year, respectively.

Although variations from year to year are small, a recent study (ETC/ACM, 2018c) assessed the long-term evolution of the European population exposure's to $PM_{2.5}$ concentration since 1990 and the associated premature deaths. Different data-sets were used and the ensemble of all datasets indicates a median decrease in premature mortality of about 60% in Europe, attributed to exposure to $PM_{2.5}$ between 1990 and 2015. This reflects a similar decrease in the European population's exposure to $PM_{2.5}$.

Exposure and impacts on European ecosystems

Air pollution also damages vegetation and ecosystems. It leads to several important environmental impacts, which affect vegetation and fauna directly, as well as the quality of water and soil, and the ecosystem services they support. The most harmful air pollutants in terms of damage to ecosystems are O_3, ammonia (NH_3) and nitrogen oxides (NO_x).

The latest estimates of vegetation exposure to O_3 indicate that the EU target value for protection of vegetation from O_3 was exceeded in 2015 ([1]) in about 30 % of the agricultural land area of the EU-28, and in 31 % of all the European countries considered. The long-term objective for the protection of vegetation from O_3 was exceeded in 79 % of the EU-28 (80 % of all European) agricultural area. The United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (CLRTAP) critical level for the protection of forests was exceeded in 61 % of the EU-28 (60 % of all European) forest area in 2015.

([1]) The methodology uses maps of interpolated air pollutant concentrations, with information on the spatial distribution of concentrations from the European Monitoring and Evaluation Programme (EMEP) model. At the time of drafting this report, the most up-to-date data from the EMEP model were used (2015).

It is estimated that about 61 % of the European ecosystem area and 72 % of the EU-28 ecosystem area remained exposed to air pollution levels exceeding eutrophication limits in 2015.

Finally, exceedances of the critical loads for acidification occurred over 5 % of the European ecosystem area and 6 % of the EU-28 ecosystem area.

Focus on tropospheric ozone

O_3 is a secondary pollutant formed in the troposphere by complex chemical reactions following emissions of precursor gases such as NOx and VOCs. The highest concentrations occur mainly in southern Europe. It affects both human health and ecosystems. In the Mediterranean basin, different mechanisms cause high O_3 episodes. Among these mechanisms are transport of O_3 from other regions, local production of O_3, and vertical recirculation from higher atmospheric layers. Regional transport is more frequent in the eastern part of the basin and local production in the western part. This has implications from the point of view of mitigation strategies to reduce O_3 impacts.

Despite the fact that O_3 precursor emissions declined in the EU-28 between 2000 and 2016 by about 40 %, mixed trends are found for O_3 concentrations depending on the metrics. However, O_3 peaks have declined over Europe since 2000. This decline has been mainly due to a reduction in the precursors emissions and, to a lesser extent, to meteorological conditions.

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1 Introduction

1.1 Background

Air pollution is a global threat leading to large impacts on health and ecosystems. Emissions and concentrations have increased in many areas worldwide. When it comes to Europe, air quality remains poor in many areas, despite reductions in emissions and ambient concentrations.

Effective action to reduce air pollution and its impacts requires a good understanding of its causes, how pollutants are transported and transformed in the atmosphere, how the chemical composition of the atmosphere changes over time, and how pollutants impact humans, ecosystems, the climate and subsequently society and the economy. To curb air pollution, collaboration and coordinated action at international, national and local levels must be maintained, in coordination with other environmental, climate and sectoral policies. Holistic solutions involving technological development, structural changes and behavioural changes are also needed, together with an integrated multidisciplinary approach.

Air pollution is perceived as the second biggest environmental concern for Europeans after climate change (European Commission, 2017b) and people expect the authorities to implement effective measures to reduce air pollution and its effects.

1.2 Objectives and coverage

This report presents an updated overview and analysis of air quality in Europe ([2]) and is focused on the state of air quality in 2016. The evaluation of the status of air quality is based on officially reported ambient air measurements (see Box 1.1), in conjunction with officially reported data on anthropogenic emissions and their evolution over time. Parts of the assessment also rely on air quality modelling.

In addition, the report includes an overview of the latest findings and estimates of the effects of air pollution on health (including the evolution, since 1990, of the effects attributed to exposure to particulate matter (PM) with a diameter of 2.5 μm or less ($PM_{2.5}$)), and of ecosystems' exposure to air pollution.

The report reviews progress towards meeting the air quality standards (see Tables 1.1 and 1.2) established in the two Ambient Air Quality Directives presently in force (EU, 2004, 2008) and the long-term objectives of achieving levels of air pollution that do not lead to unacceptable harm to human health and the environment, as presented in the latest two European Environment Action Programmes (EU, 2002, 2013), moving closer to the World Health Organization (WHO) air quality guidelines (WHO, 2000, 2006a) (see Table 1.3).

This year's report looks into tropospheric ozone (O_3) pollution in some more detail. The development and causes of O_3 pollution in Europe, and especially in the Mediterranean, are analysed, as along with some abatement strategies. Tropospheric O_3 is an air pollutant with significant impacts on health, ecosystems, crops and forests, as well as climate. O_3 is a secondary pollutant formed in the presence of sun-light and governed by complex formation, reaction, transport and deposition mechanisms. As a result, the design of air quality policies to efficiently

([2]) The report focuses as much as possible on the EEA-39 countries, that is:
- the 28 Member States of the European Union (EU), or EU-28 — Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom;
- plus the five other member countries of the European Environment Agency (EEA) — Iceland, Liechtenstein, Norway, Switzerland and Turkey — that, together with the EU-28, form the EEA-33;
- plus the six cooperating countries of the EEA — Albania, Bosnia and Herzegovina, the former Yugoslav Republic of Macedonia, Kosovo under United Nations Security Council Resolution 1244/99, Montenegro and Serbia — that, together with the EEA-33, form the EEA-39 countries.

Finally, some information also covers other smaller European countries such as Andorra, Monaco and San Marino.

abate ambient air O_3 concentrations is also a complex task. Since the second half of the 1990s, European policies have been in place to limit emissions of O_3 precursors and regulate ambient concentrations, but measurements indicate that in certain regions of Europe the decline in O_3 is less than expected. Consequently, several questions have been raised regarding the underlying reasons, which are complex and related to meteorological conditions, emissions of precursors and long-range transport of O_3.

1.3 Effects of air pollution

1.3.1 Human health

Air pollution is a major cause of premature death and disease and is the single largest environmental health risk in Europe (Lim et al., 2012; WHO, 2014, 2016a; GBD 2016 Risk Factors Collaborators, 2017; HEI, 2018), causing around 400 000 premature deaths per year. Heart disease and stroke are the most common reasons for premature death attributable to air pollution, followed by lung diseases and lung cancer (WHO, 2014). The International Agency for Research on Cancer has classified air pollution in general, as well as PM as a separate component of air pollution mixtures, as carcinogenic (IARC, 2013).

Both short- and long-term exposure of children and adults to air pollution can lead to reduced lung function, respiratory infections and aggravated asthma. Maternal exposure to ambient air pollution is associated with adverse impacts on fertility, pregnancy, new-borns and children (WHO, 2005, 2013b). There is also emerging evidence that exposure to air pollution is associated with new-onset type 2 diabetes in adults, and it may be linked to obesity, systemic inflammation, ageing, Alzheimer's disease and dementia (RCP, 2016, and references therein; WHO, 2016b).

Box 1.1 Ambient air measurements

The analysis of concentrations in relation to the defined EU and WHO standards is based on measurements at fixed sampling points. Only measurement data received by 4 June 2018 ([3]) were included in the analysis and, therefore, the maps, figures and tables reflect this data. Data officially reported after that date are regularly updated in the Air Quality e-Reporting Database (EEA, 2018a).

Fixed sampling points in Europe are situated at four types of sites:

- traffic-oriented locations ('traffic');
- urban and suburban background (non-traffic, non-industrial) locations ('urban');
- industrial locations (or other, less defined, locations: 'other'); and
- rural background sites ('rural').

For most of the pollutants (sulphur dioxide (SO_2), nitrogen dioxide (NO_2), O_3, PM and carbon monoxide (CO)), monitoring stations have to fulfil the criterion of reporting more than 75 % of valid data out of all the possible data in a year to be included in this assessment. The Ambient Air Quality Directive (EU, 2008) sets the objective for them of a minimum data capture of 90 % but, for assessment purposes, the more relaxed coverage of 75 % allows more stations to be taken into account without a significant increase in monitoring uncertainties (ETC/ACM, 2012).

For benzene (C_6H_6), the required amount of valid data for the analysis is 50 %. For toxic metals (arsenic (As), cadmium (Cd), nickel (Ni) and lead (Pb)) and benzo[*a*]pyrene (BaP), it is 14 % (according to the air quality objectives for indicative measurements; EU, 2004, 2008).

The assessment in this report does not take into account the fact that Member States may use supplementary assessment modelling. Furthermore, in the cases of PM and SO_2, nor does it account for the fact that the Ambient Air Quality Directive (EU, 2008) provides the Member States with the possibility of subtracting contributions to the measured concentrations from natural sources and winter road sanding/salting.

([3]) Italy, however, resubmitted data after this date. The new data have been considered. A change of status has occurred in four stations: two stations have changed from above to below the Pb limit value; and two stations have changed from above to below the BaP target value.

While this report focuses only on ambient (outdoor) air quality, indoor air pollution also poses considerable impacts on health, especially in homes that use open fires for heating and cooking (Lim et al., 2012; WHO, 2013b; RCP, 2016).

1.3.2 Ecosystems

Air pollution has several important environmental impacts and may directly affect vegetation and fauna, as well as the quality of water and soil and

Table 1.1 Air quality standards for the protection of health, as given in the EU Ambient Air Quality Directives

Pollutant	Averaging period	Legal nature and concentration	Comments
PM_{10}	1 day	Limit value: 50 µg/m³	Not to be exceeded on more than 35 days per year
	Calendar year	Limit value: 40 µg/m³	
$PM_{2.5}$	Calendar year	Limit value: 25 µg/m³	
		Exposure concentration obligation: 20 µg/m³	Average Exposure Indicator (AEI) ([a]) in 2015 (2013-2015 average)
		National Exposure reduction target: 0-20 % reduction in exposure	AEI ([a]) in 2020, the percentage reduction depends on the initial AEI
O_3	Maximum daily 8-hour mean	Target value: 120 µg/m³	Not to be exceeded on more than 25 days/year, averaged over 3 years ([b])
		Long-term objective: 120 µg/m³	
	1 hour	Information threshold: 180 µg/m³	
		Alert threshold: 240 µg/m³	
NO_2	1 hour	Limit value: 200 µg/m³	Not to be exceeded on more than 18 hours per year
		Alert threshold: 400 µg/m³	To be measured over 3 consecutive hours over 100 km² or an entire zone
	Calendar year	Limit value: 40 µg/m³	
BaP	Calendar year	Target value: 1 ng/m³	Measured as content in PM_{10}
SO_2	1 hour	Limit value: 350 µg/m³	Not to be exceeded on more than 24 hours per year
		Alert threshold: 500 µg/m³	To be measured over 3 consecutive hours over 100 km² or an entire zone
	1 day	Limit value: 125 µg/m³	Not to be exceeded on more than 3 days per year
CO	Maximum daily 8-hour mean	Limit value: 10 mg/m³	
C_6H_6	Calendar year	Limit value: 5 µg/m³	
Pb	Calendar year	Limit value: 0.5 µg/m³	Measured as content in PM_{10}
As	Calendar year	Target value: 6 ng/m³	Measured as content in PM_{10}
Cd	Calendar year	Target value: 5 ng/m³	Measured as content in PM_{10}
Ni	Calendar year	Target value: 20 ng/m³	Measured as content in PM_{10}

Notes: ([a]) AEI: based upon measurements in urban background locations established for this purpose by the Member States, assessed as a 3-year running annual mean.

([b]) In the context of this report, only the maximum daily 8-hour means in 2016 are considered, so no average over the period 2014-2016 is presented.

Sources: EU, 2004, 2008.

Table 1.2 Air quality standards, for the protection of vegetation, as given in the EU Ambient Air Quality Directive and the CLRTAP

Pollutant	Averaging period	Legal nature and concentration	Comments
O_3	AOT40 ([a]) accumulated over May to July	Target value, 18 000 µg/m³.hours	Averaged over 5 years ([b])
		Long-term objective, 6 000 µg/m³.hours	
	AOT40 ([a]) accumulated over April to September	Critical level for the protection of forests: 10 000 µg/m³.hours	Defined by the CLRTAP
NO_x	Calendar year	Vegetation critical level: 30 µg/m³	
SO_2	Winter	Vegetation critical level: 20 µg/m³	1 October to 31 March
	Calendar year	Vegetation critical level: 20 µg/m³	

Notes: ([a]) AOT40 is an indication of accumulated ozone exposure, expressed in µg/m³.hours, over a threshold of 40 ppb. It is the sum of the differences between hourly concentrations > 80 µg/m³ (40 ppb) and 80 µg/m³ accumulated over all hourly values measured between 08:00 and 20:00 (Central European Time).

([b]) In the context of this report, only yearly AOT40 concentrations are considered, so no average over 5 years is presented.

Sources: EU, 2008; UNECE, 2011.

Table 1.3 WHO air quality guidelines (AQG) and estimated reference levels (RL) ([a])

Pollutant	Averaging period	AQG	RL	Comments
PM_{10}	1 day	50 µg/m³		99th percentile (3 days per year)
	Calendar year	20 µg/m³		
$PM_{2.5}$	1 day	25 µg/m³		99th percentile (3 days per year)
	Calendar year	10 µg/m³		
O_3	Maximum daily 8-hour mean	100 µg/m³		
NO_2	1 hour	200 µg/m³		
	Calendar year	40 µg/m³		
BaP	Calendar year		0.12 ng/m³	
SO_2	10 minutes	500 µg/m³		
	1 day	20 µg/m³		
CO	1 hour	30 mg/m³		
	Maximum daily 8-hour mean	10 mg/m³		
C_6H_6	Calendar year		1.7 µg/m³	
Pb	Calendar year	0.5 µg/m³		
As	Calendar year		6.6 ng/m³	
Cd	Calendar year	5 ng/m³ ([b])		
Ni	Calendar year		25 ng/m³	

Notes: ([a]) As WHO has not set an AQG for BaP, C_6H_6, As and Ni, the reference level was estimated assuming an acceptable risk of additional lifetime cancer risk of approximately 1 in 100 000.

([b]) AQG set to prevent any further increase of Cd in agricultural soil, likely to increase the dietary intake of future generations.

Sources: WHO, 2000, 2006a.

the ecosystem services that they support. For example, nitrogen oxides (NO_x, the sum of nitrogen monoxide (NO) and NO_2) and ammonia (NH_3) emissions disrupt terrestrial and aquatic ecosystems by introducing excessive amounts of nutrient nitrogen. This leads to eutrophication, which is an oversupply of nutrients that can lead to changes in species diversity and to invasions of new species. NO_x, together with SO_2, also contribute to the acidification of soil, lakes and rivers, causing biodiversity loss. Finally, ground-level O_3 damages agricultural crops, forests and plants by reducing their growth rates and has negative impacts on biodiversity and ecosystem services.

1.3.3 Climate change

Air pollution and climate change are intertwined. Several air pollutants are also climate forcers, which have a potential impact on climate and global warming in the short term. Tropospheric O_3 and black carbon (BC), a constituent of PM, are examples of air pollutants that are short-lived climate forcers and that contribute directly to global warming. Other PM components, such as organic carbon, ammonium (NH_4^+), sulphate (SO_4^{2-}) and nitrate (NO_3^-), have a cooling effect (IPCC, 2013). In addition, changes in weather patterns due to climate change may alter the transport, dispersion, deposition and formation of air pollutants in the atmosphere. Increasing temperature, for instance, will increase the emissions of biogenic volatile organic compounds (VOCs), which are O_3 precursors, and emissions from wildfires and dust events. In addition to its warming effect, O_3 impairs vegetation growth, as indicated above, by reducing vegetation's uptake of carbon dioxide (CO_2). Climate change alters environmental conditions (e.g. temperature, pH) that modify the bio-availability of pollutants (e.g. metals and POPs), the exposure, uptake and sensitivity of species to pollutants (Noyes et al., 2009; Staudt et al., 2013). Consequently, climate change may magnify the adverse environmental effects of pollutants, including O_3, toxic metals and persistent organic pollutants (POPs) (Hansen and Hoffman, 2011; Staudt et al., 2013).

Air quality and climate change should be tackled jointly using policies and measures that have been developed through an integrated approach. These integrated policies would avoid the negative impact of climate policies on air quality, or vice versa, which has already been evidenced. Examples are the negative impacts on air quality arising from the subsidising of diesel cars (which have lower CO_2 but higher PM and NO_x emissions) and from the increased use of biomass combustion without adequate emission controls.

1.3.4 The built environment and cultural heritage

Air pollution can damage materials, properties, buildings and artworks, including Europe's culturally most significant buildings. The impact of air pollution on cultural heritage materials is a serious concern because it can lead to the loss of parts of our history and culture. Damage includes corrosion (caused by acidifying compounds), biodegradation and soiling (caused by particles), and weathering and fading of colours (caused by O_3).

A recent paper (Tidblad et al., 2017) found that corrosion and pollution decreased significantly from 1987 to 2014, even though the rate of decrease slowed down after 1997. SO_2 levels and the corrosion of carbon steel and copper decreased after 1997, especially in urban areas, while the corrosion or soiling of other materials (apart from zinc) decreased very little, if at all, after 1997.

1.3.5 Economic impacts

The effects of air pollution on health, crop and forest yields, ecosystems, the climate and the built environment also entail considerable market and non-market costs. The market costs of air pollution include reduced labour productivity, additional health expenditure, and crop and forest yield losses. The Organisation for Economic Co-operation and Development (OECD) projects that these costs will increase to reach about 2 % of European gross domestic product (GDP) in 2060 (OECD, 2016), leading to a reduction in capital accumulation and a slowdown in economic growth.

Non-market costs are those associated with increased mortality and morbidity (illness causing, for example, pain and suffering), degradation of air and water quality and consequently the health of ecosystems, as well as climate change.

In 2015, more than 80 % of the total costs (market and non-market) of outdoor air pollution in Europe were related to mortality, while market costs were less than 10 %, (OECD, 2016). OECD (2016) estimates that the total costs for the OECD region amount to USD 1 280 (around EUR 1 100) per capita for 2015 and USD 2 880 to USD 2 950 (around EUR 2 480 to 2 540) per capita for 2060, corresponding to about 5 % of income in both 2015 and 2060. The non-market costs of outdoor air pollution amount to USD 1 200 (around EUR 1 030) per capita in 2015 and are projected to increase to USD 2 610-2 680 (around EUR 2 250-2 310) in 2060 in the OECD region.

1.4 International policy

Increased recognition of the effects and costs of air pollution has lead international organisations, national and local authorities, industry and non-governmental organisations (NGOs) to take action.

At international level, the United Nations Economic Commission for Europe (UNECE), the WHO and UN Environment, among others, have recently decided on global actions to address the long-term challenges of air pollution.

The UNECE Convention on Long-range Transboundary Air Pollution (LRTAP Convention; UNECE, 1979) addresses emissions of air pollutants via its various protocols, among which the 2012 amended Gothenburg Protocol is key in reducing emissions of selected pollutants across the pan-European region. The UNECE Eighth Environment for Europe Ministerial Conference, held in Batumi, Georgia, in June 2016, approved the declaration 'Greener, cleaner, smarter!' (UNECE, 2016). It recognised air pollution as a serious environmental health threat and made a commitment to improve air quality by (1) integrating air pollution reduction measures into financial, development and other sectoral policies as appropriate, (2) cooperation to address transboundary impacts and enhanced policy coordination, and (3) coherence at national and regional levels. It also pledged to ensure adequate monitoring of air pollution as well as public access to relevant information.

The WHO Regional Office for Europe held its Sixth Ministerial Conference on Environment and Health in Ostrava, Czechia, in June 2017. The declaration of this conference (WHO, 2017a) resolved, among other things, to protect and promote people's health and well-being by actively improving air quality to meet the WHO air quality guidelines (WHO, 2000, 2006a). These guidelines (see Table 1.3) are designed to offer guidance in reducing the health impacts of air pollution and are based on expert evaluation of current scientific evidence. They are currently under review.

The United Nations Environment Assembly (UNEA) of the United Nations Environment Programme, in its Resolution 1/7 on air quality, 2014 (UNEP, 2014), requested that UN Environment support governments in their efforts to implement the resolution through capacity-building activities; awareness-raising; strengthened cooperation on air pollution; monitoring and assessment of air quality issues; and undertaking global, regional and sub-regional assessments. In the 2017 meeting, Resolution 3/8 (UNEP, 2017) urged the Member States to put in place policies and measures to prevent and reduce air pollution from significant sources.

Air quality is closely linked to the Sustainable Development Goals ([4]) (SDGs) and several of the goals, concerning health, welfare and urbanisation, implicitly include air quality issues . For instance, SDG-3 (Good health and well-being) targets substantially reducing the number of deaths and illnesses caused by air pollution by 2030, and SDG-11 (Sustainable cities and communities) targets reducing the adverse per capita environmental impact of cities by 2030, through paying particular attention to air quality.

1.5 European Union legislation

The EU has been working for decades to improve air quality by controlling emissions of harmful substances into the atmosphere, improving fuel quality, and integrating environmental protection requirements into the transport, industrial and energy sectors. Figure 1.1 illustrates the framework of the EU's clean air policy, based on three main pillars (European Commission, 2018a):

1. Ambient air quality standards set out in the Ambient Air Quality Directives (EU, 2004, 2008) (see tables 1.1 and 1.2), requiring the Member States to adopt and implement air quality plans and meet standards in order to protect human health and the environment;

2. National emission reduction targets established in the National Emission Ceilings (NEC) Directive (EU, 2016), requiring Member States to develop National Air Pollution Control Programmes by 2019 in order to comply with their emission reduction commitments;

3. Emission and energy efficiency standards for key sources of air pollution, from vehicle emissions to products and industry. These standards are set out in EU legislation targeting industrial emissions, emissions from power plants, vehicles and transport fuels, as well as the energy performance of products and non-road mobile machinery ([5]).

The Seventh Environment Action Programme, 'Living well, within the limits of our planet' (EU, 2013)

([4]) These goals were set in the United Nations' (UN) 2030 Agenda for Sustainable Development (UN, 2015b), covering the social, environmental and economic development dimensions at a global level (UN, 2015a).

([5]) For more information on the specific legislation, please check http://ec.europa.eu/environment/air/quality/existing_leg.htm.

recognises the long-term goal within the EU to achieve 'levels of air quality that do not give rise to significant negative impacts on, and risks to, human health and the environment'. To meet this goal, effective air quality policies require cooperation and action at global, European, national and local levels. In line with the principle of subsidiarity, policies must be developed at national, regional and local levels, implementing measures tailored to specific needs and circumstances.

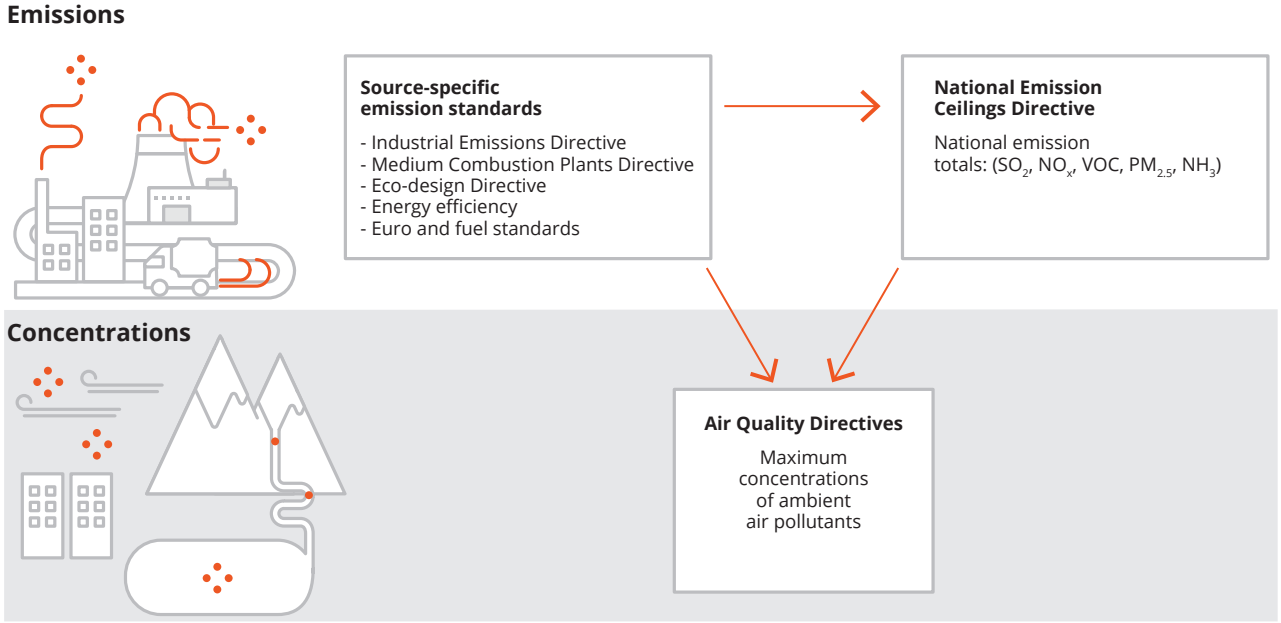
The Clean Air Programme for Europe (CAPE), published by the European Commission in late 2013 (European Commission, 2013), aims to ensure full compliance with existing legislation by 2020 at the latest, and to further improve Europe's air quality, so that by 2030 the number of premature deaths is reduced by half when compared with 2005. Following the proposals made in this context, the NEC Directive was revised and approved in 2016 (see bullet point 2 above) and a new directive (EU, 2015) on the limitation of emissions of certain pollutants from medium combustion plants was approved in 2015. It regulates pollutant emissions from the combustion of fuels in plants with a rated thermal input equal to or greater than 1 megawatt (MWth) and less than 50 MWth.

In addition, the EU is supporting and facilitating the Member States to take the measures necessary to meet their targets, and the enforcement action to help ensure that the common objective of clean air for all Europeans is achieved across the EU. This includes the EU Urban Agenda and Urban Innovative Actions, which facilitate cooperation with and among city actors to address air pollution in urban areas across the EU.

The CAPE also envisages a regular update of the impact assessment analysis, to track progress towards the objectives of the Ambient Air Quality Directives. In 2018, the European Commission published the *First clean air outlook* (European Commission, 2018b). It concluded that the package of measures that has been adopted since 2013 is expected to surpass the health impact reduction by 2030, as anticipated in the CAPE. However, it also recognises that there is an urgent short-term need to take decisive action to achieve the objectives of the Ambient Air Quality Directives, at all governance levels.

In relation to the Ambient Air Quality Directives (EU, 2004, 2008), the European Commission started a 2-year process in 2017 to fitness check them. The process aims to examine the performance of the Ambient Air Quality Directives. It builds on the analysis underlying the CAPE and will draw on experience in all Member States, focusing on the period 2008-2018. It will look at the fitness-for-purpose of all the Directives' provisions, and in particular the monitoring and assessment methods, the air quality standards, the provisions on public information, and the extent to which the Directives have facilitated action to prevent or reduce adverse impacts. Administrative costs, overlaps and/or synergies, gaps, inconsistencies and/or potentially obsolete measures will also be addressed, as well as the coherence of air quality governance between EU, Member States, regional and local levels. Under current planning, the fitness check will be concluded in 2019 (European Commission, 2017a).

Figure 1.1 EU clean air policy – the policy framework



In addition to the specific legislation on air, the European Commission prioritises a strong Energy Union and a clean, safe and connected mobility, and is committed to meeting the targets of the Paris Agreement on decarbonisation. It has, inter alia, introduced measures on: (1) cleaner vehicles, i.e. new CO_2 standards for cars and vans and, for the first time, trucks; (2) updating road pricing, to encourage less polluting modes of transport and to ease traffic congestion; and (3) promoting alternative energies, such as electric cars, with new measures to improve the deployment of charging infrastructure and an action plan for batteries (European Commission, 2018a).

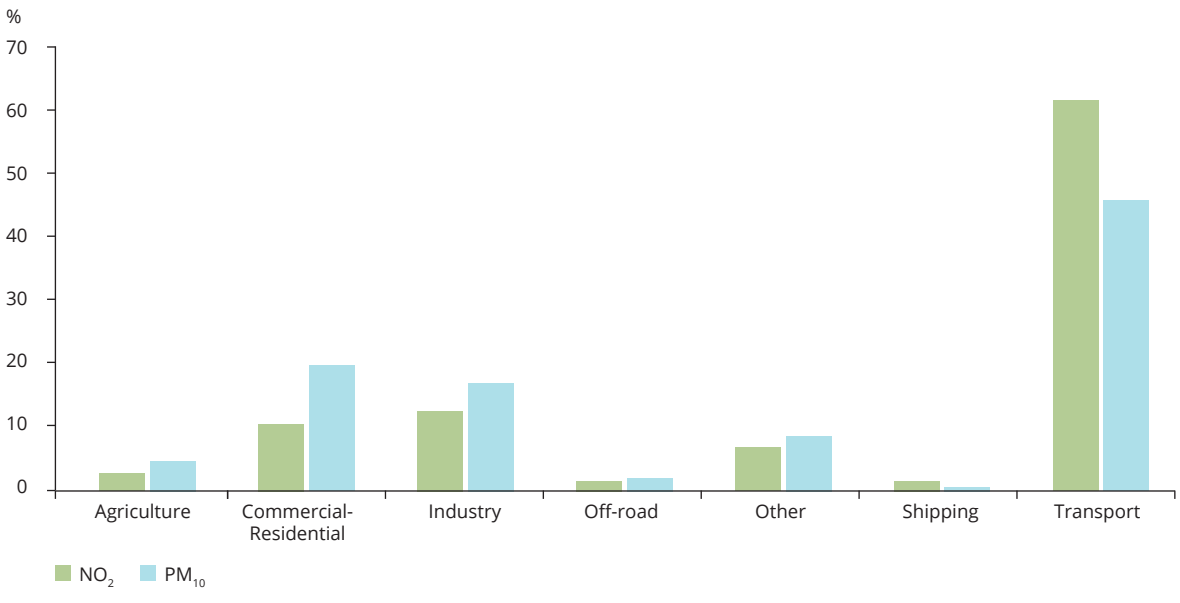
Europe is actively addressing the issue of toxic metal releases to the environment through the implementation of the Industrial Emission Directive (2010/75/EU), the CLRTAP 1998 Protocol on Heavy Metals, and the Mercury Regulation (2017/852/EU) as a response to the Minamata Convention on Mercury (UN, 2013). In addition, the Water Framework Directive (2000/60/EC) establishes a requirement for achieving good ecological and chemical status in European waters. This includes targets for reducing heavy metal concentrations.

1.6 National and local measures to improve air quality in Europe

Air quality plans and measures to reduce air pollutant emissions and improve air quality have been implemented throughout Europe and form a core element in air quality management. The Ambient Air Quality Directives (EU, 2004, 2008) set the obligation of developing and implementing air quality plans and measures for zones and agglomerations where concentrations of pollutants exceed the EU standards (and of maintaining quality where it is good, see also Section 1.5).

Most of the measures reported by the Member States under the Ambient Air Quality Directives (EU, 2004, 2008) over the last 3 years are aimed at reducing concentrations of and the number of exceedances of the limit values of PM_{10} and NO_2 (EEA, 2018b). In general, the road transport sector is the largest contributor to total nitrogen dioxide emissions in the EU, while fuel combustion in the commercial, institutional and households sector is the largest contributor to overall primary particulate matter emissions, particularly in some eastern European countries (see Chapter 2). Most reported measures address the road transport sector (Figure 1.2). The main measures related to traffic are encouraging a shift among transport modes; land use planning to ensure sustainable transport facilities; improving public transport; and public procurement. The second and third most-targeted sectors are commercial and residential combustion, and industry in the case of PM_{10}, and industry, and commercial and residential combustion for NO_2. Measures targeting industry and the commercial and residential combustion sectors are mainly targeting a shift towards low-emission fuels, emission control equipment and retrofitting. Lastly, measures focusing on public information are important in all cases. They typically aim to give the public targeted information about individual actions that they can take to reduce air pollution. The local administrative level is responsible for the majority of planning and implementation with regard to these measures (EEA, 2018h).

Figure 1.2 Sectors addressed by the measures reported by the EU-28 Member States for PM_{10} and NO_2



Source: EEA, 2018h.

2 Sources and emissions of air pollutants

Air pollutants may be categorised as primary or secondary. Primary pollutants are directly emitted to the atmosphere, whereas secondary pollutants are formed in the atmosphere from precursor pollutants through reactions. Air pollutants may have a natural, anthropogenic or mixed origin, depending on their sources or the sources of their precursors.

Key primary air pollutants include PM, BC, sulphur oxides (SO_x), NO_x (which includes both NO and NO_2), NH_3, CO, methane (CH_4), non-methane volatile organic compounds (NMVOCs) including C_6H_6 ([6]), certain metals and polycyclic aromatic hydrocarbons (PAH, including BaP).

Key secondary air pollutants are PM (formed in the atmosphere), O_3, NO_2 and a number of oxidised VOCs. Key precursor gases for secondary PM are SO_2, NO_x, NH_3 and VOCs. The gases NH_3, SO_2 and NO_x react in the atmosphere to form NH_4^+, SO_4^{2-} and NO_3^- compounds. These compounds form new particles in the air or condense onto pre-existing ones to form secondary PM (also called secondary inorganic aerosols). Certain NMVOCs are oxidised to form less volatile compounds, which form secondary organic aerosols. Ground-level (tropospheric) O_3 is not directly emitted into the atmosphere. Instead, it is formed from chemical reactions in the presence of sunlight, following emissions of precursor gases, mainly NO_x, NMVOCs and CH_4. These precursors can be of both natural (biogenic) and anthropogenic origin. NO_x also depletes tropospheric O_3 as a result of the titration reaction with the emitted NO to form NO_2 and oxygen (O_3 formation cycle, see also Chapter 5).

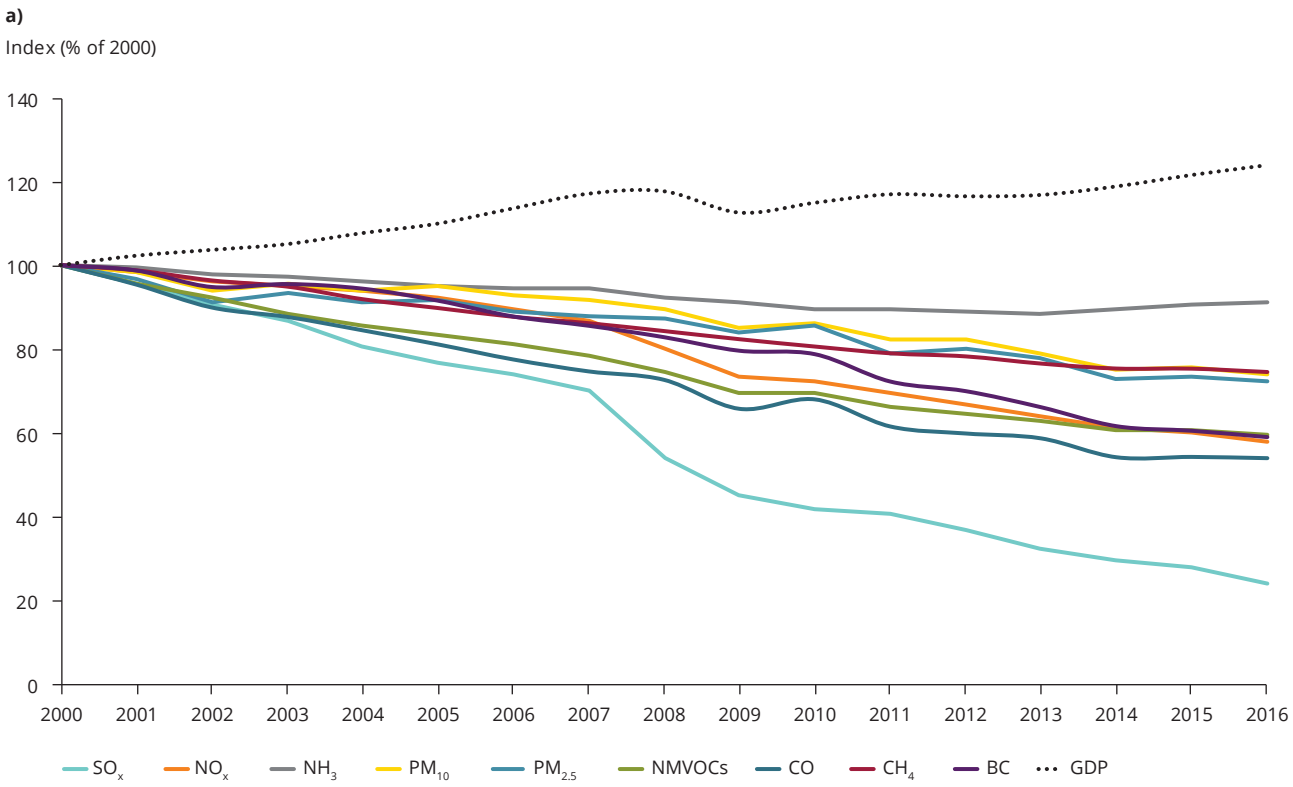
2.1 Total emissions of air pollutants

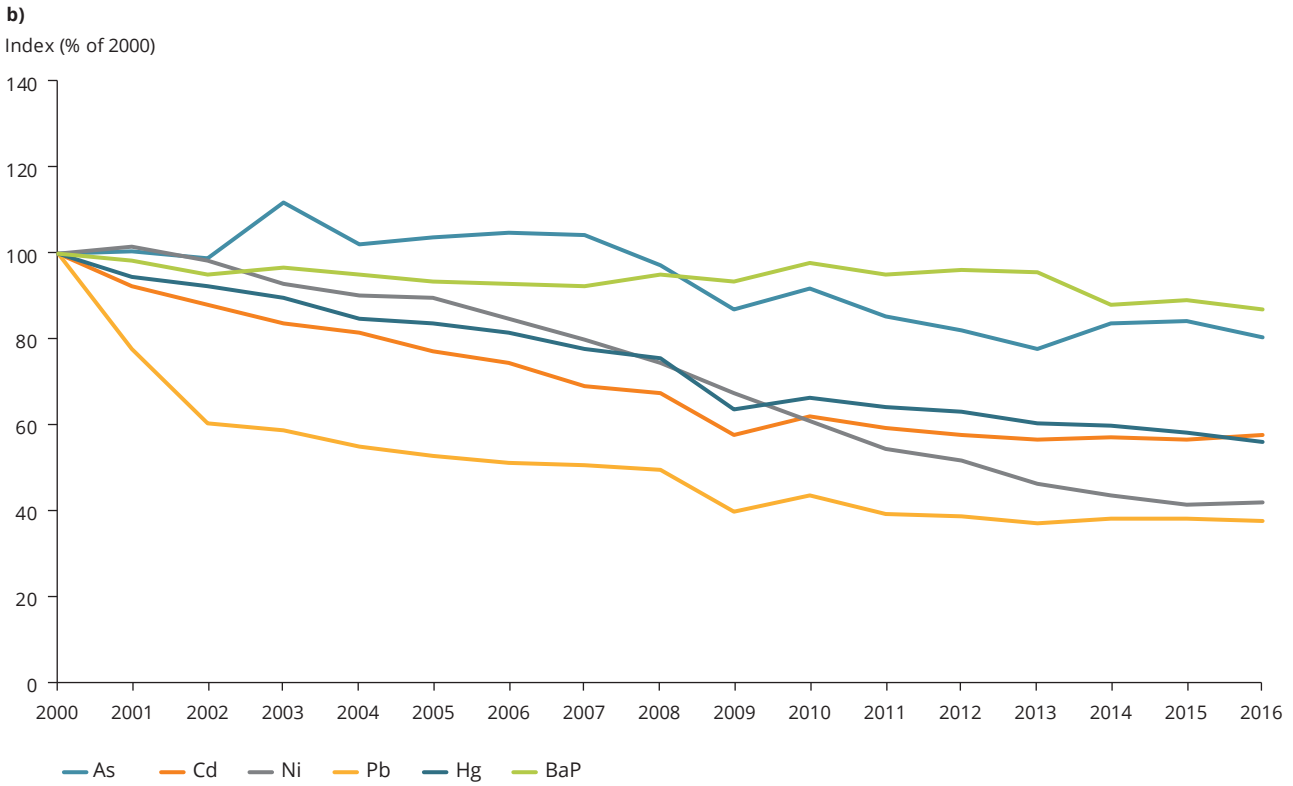
Figure 2.1 shows the total emissions of pollutants in the EU-28, indexed as a percentage of their value in the reference year 2000. As can be seen, emissions of all primary and precursor pollutants contributing to ambient air concentrations of PM, O_3 and NO_2, as well as As, Cd, Ni, Pb, Hg and BaP ([7]), decreased between 2000 and 2016 in the EU-28 (Figure 2.1) and the EEA-33 ([8]). SO_2 emissions have exhibited the largest reduction (76 % in the EU-28 and 62 % in the EEA-33) since 2000, while NH_3 emissions have exhibited the smallest reductions (9 % in the EU-28 and 5 % in the EEA-33). Furthermore, in the period 2013-2016, NH_3 emissions have increased in the agriculture sector by about 3% (EEA, 2018e). Generally, reductions of emissions in the EU-28 and EEA-33 were similar. There were slightly larger reductions in the EU-28 than in the EEA-33, with the exception of As, BaP, Hg and $PM_{2.5}$ where reductions were slightly higher in the EEA-33 than in the EU-28 (although here the differences were less than 1.2 %).

In recent years, a large proportion of emissions has shown significant absolute decoupling ([9]) from economic activity, which is desirable for both environmental and productivity gains. This is indicated by a reduction in EU-28 air pollutant emissions contrasting with an increase in EU-28 GDP ([10]) (Eurostat, 2018a), which effectively means that there are now fewer emissions for each unit of GDP produced per year. The greatest decoupling has been for SO_x, CO, NO_x, certain metals (Ni, Pb, Cd, Hg) and organic species (NMVOC and BC), for which emissions

([6]) There is no separate emission inventory for C_6H_6, but it is included as a component of NMVOC.
([7]) The emissions reported from Portugal for the activity 'asphalt blowing in refineries' were not taken into account to ensure consistency between nationally reported data (they were not reported by any other country).
([8]) The analysis of the development of emissions in Europe is based on emissions reported by the countries (EEA, 2018e, 2018c). The nominal increase or decrease in reported emissions is analysed, not statistical trends.
([9]) 'Absolute decoupling' is when a variable is stable or decreasing when the growth rate of the economic driving force is growing, while 'relative decoupling' is when the growth rate of the variable is positive but less than the growth rate of the economic variable (OECD, 2002).
([10]) Based on chain-linked volumes (2010), in euros, to obtain a time-series adjusted for price changes (inflation/deflation).

Figure 2.1 **Development in EU-28 emissions, 2000-2016 (% of 2000 levels): a) SO_x, NO_x, NH_3, PM_{10}, $PM_{2.5}$, NMVOCs, CO, CH_4 and BC. Also shown for comparison is EU-28 gross domestic product (GDP expressed in chain-linked volumes (2010), % of 2000 level); b) As, Cd, Ni, Pb, Hg and BaP**





Notes: CH_4 emissions are total emissions (Integrated Pollution Prevention and Control sectors 1-7) excluding sector 5: Land use, land-use change and forestry. The present emission inventories include only anthropogenic VOC emissions.

Sources: EEA, 2018c, 2018e; Eurostat, 2018a.

per unit of GDP were reduced by over 50 % between the years 2000 and 2016. A decoupling of emissions from economic activity may be due to a combination of factors, such as increased regulation and policy implementation, fuel switching, technological improvements and improvements to energy or process efficiencies (see Sections 1.5 and 1.6).

2.2 Sources of regulated pollutants by emissions sector

The main sectors contributing to emissions of air pollutants in Europe are:

- transport, split into:
  - road;
  - non-road (which includes, for example, air, rail, sea and inland water transport);
- commercial, institutional and households;
- energy production and distribution;
- industry, split into:
  - energy use in industry;
  - industrial processes and product use;
- agriculture; and
- waste (which includes landfill, waste incineration with heat recovery and open burning of waste).

Stationary and mobile combustion processes are the main source of many primary pollutants (e.g. NO_x, SO_x, PM, BaP, CO, C_6H_6 and toxic metals). SO_x and NO_x are primarily emitted from fuel combustion in the form of SO_2 and NO, respectively. BaP, CO and C_6H_6 are emitted as a result of the incomplete combustion of fossil fuels and biofuels. Road transport was once a major source of CO emissions, but the introduction of catalytic converters has reduced these emissions significantly. Primary PM is commonly classified as PM_{10} and $PM_{2.5}$, and is mainly derived from fuel combustion for domestic heating, power generation, etc. BC is a constituent of $PM_{2.5}$ formed from incomplete fuel combustion, with the main sources including domestic heating and transport. However, other types of emissions are also important sources of primary pollutants. For example, agriculture is the main source of CH_4 (ruminant animals in particular), followed by waste management. Industrial activity (e.g. metal processing) and energy production are key sources of toxic metal emissions to the air, which tend to originate from a small number of facilities (EEA, 2018d).

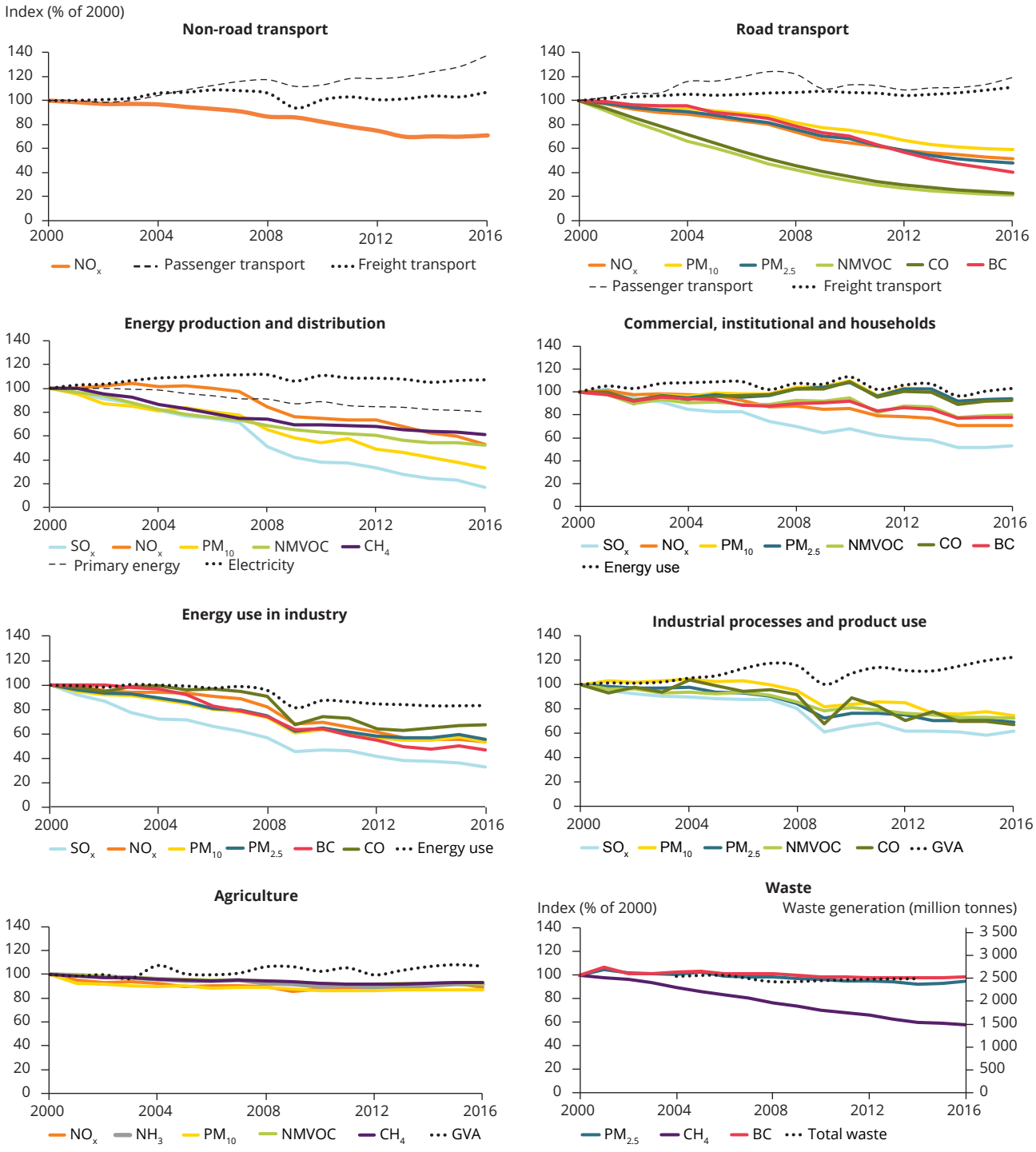
Figure 2.2 shows the evolution of SO_x, NO_x, NH_3, primary PM_{10}, primary $PM_{2.5}$, NMVOCs, CO, CH_4 and BC emissions from the main sectors in the EU-28 between the years 2000 and 2016. Similarly, Figure 2.3 shows the evolution of As, Cd, Ni, Pb and Hg, and BaP emissions. For clarity, these figures show only pollutants for which the sector contributes more than 5 % of the total EU-28 emissions. In general, significant reductions in emissions are shown across most sectors. The commercial, institutional and household, waste and agriculture sectors show the smallest reductions, and within the commercial, institutional and household sector some pollutants emissions have even increased. Changes in pollutant emissions by sector were generally similar in the EU-28 and the EEA-33.

To indicate the degrees of emission decoupling from sectoral activities within the EU-28 between 2000 and 2016, Figure 2.2 also shows the change in sectoral activity (Box 2.1) for comparison with the change in emissions over time. As with the emission data, these are expressed as an index (% relative to the year 2000) on the figures ([11]).

For both road and non-road transport sectors, emissions of key pollutants (e.g. NO_x) have decreased significantly, although transported passenger and freight volume has increased and stayed relatively constant. Policy actions have increasingly been taken to address transport-related air pollution while allowing for sectoral growth (EEA, 2017c). At EU level, this has included the regulation of emissions by setting emission standards (e.g. EURO 1-6) or by setting requirements for fuel quality. Similarly, emissions of many pollutants from industry (industrial processes and product use sector, and the energy use in industry sector), and energy production and distribution have significantly decreased since 2000, whereas the corresponding sectoral activity indicator has decreased much less (e.g. energy use in industry sector) or even increased (e.g. industrial processes and product use sector). Stationary emission sources in the industry

([11]) The waste dataset is plotted as totals on a secondary axis on the figure and not as an index (% 2000), since streamlined EU-28 data on the generation, recovery and disposal of waste has been collected only every 2 years since 2004, following the adoption of Regulation (EC) No 2150/2002 (EEA, 2015b).

Figure 2.2 **Development in EU-28 emissions from main source sectors of SO_x, NO_x, NH_3, PM_{10}, $PM_{2.5}$, NMVOCs, CO, BC and CH_4, 2000-2016 (% of 2000 levels). Also shown for comparison are key EU-28 sectoral activity statistics (% of 2000 levels) (a)**

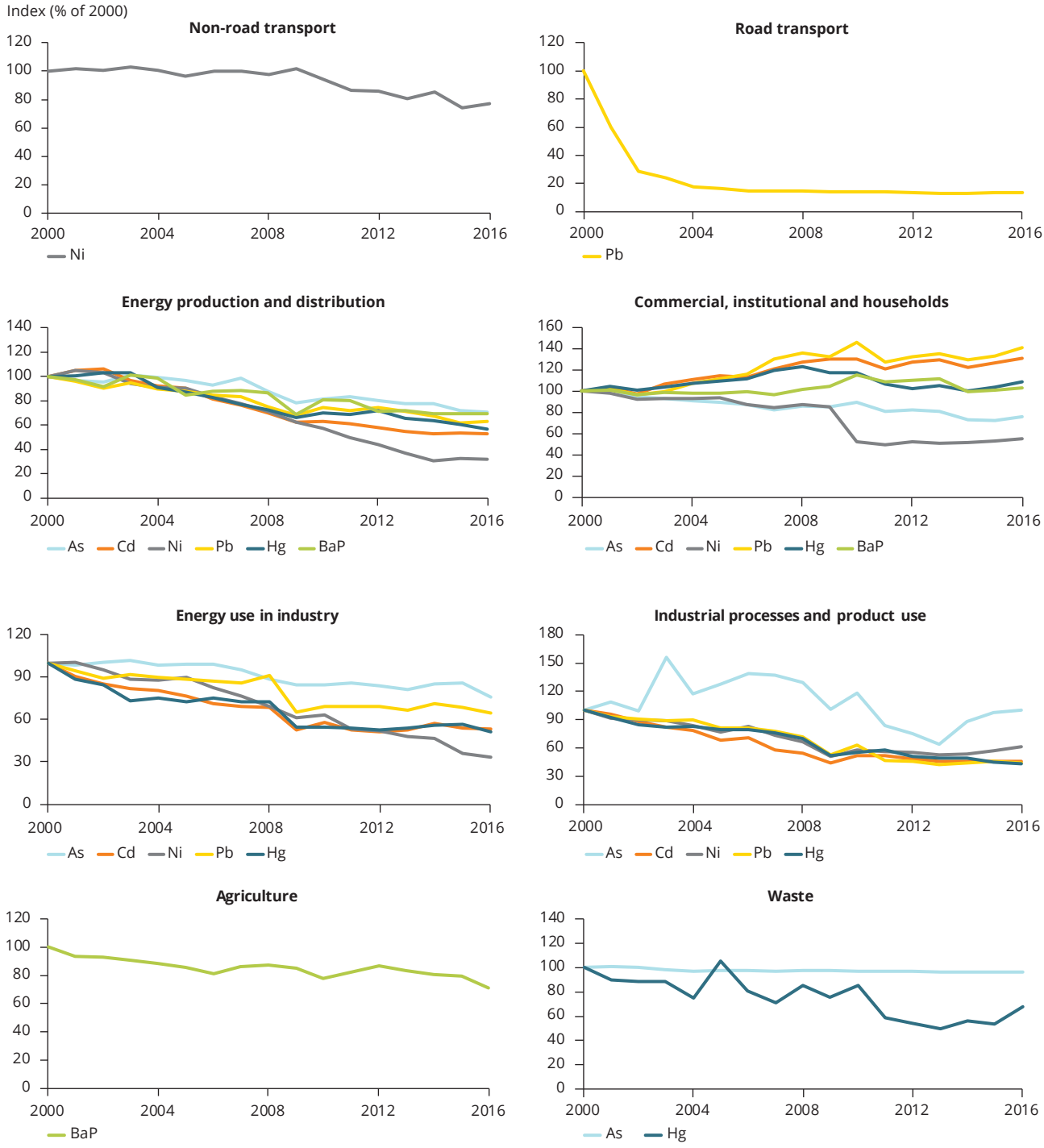


Notes: Only pollutants for which the sector contributes more than 5 % to the total pollutant emissions are shown in the figures. Also shown for comparison is key sectoral data indicative of sectoral activity. This includes passenger and freight transport volume with original units of billion passenger-kilometres and billion tonne-kilometres (road transport sector and non-road transport sector), final sectoral energy consumption with original units of, for example, TOE (commercial, institutional and household sector and energy use in industry sector), total primary energy production and total gross electricity production with original units of, for example, TOE (energy production and distribution sector), sectoral gross value added, expressed in euros in chain linked-volumes (reference year 2010) (agriculture sector and industrial processes and product use sector) and total waste generated with original units of tonne (waste sector) (see also Box 2.1).

(a) Sectoral statistics are plotted as an index (% of 2000 levels) aside from for the waste sector, where total waste generated was only available from 2004. These data are therefore plotted on a secondary (right) axis.

Sources: EEA, 2018c, 2018e; European Commission, 2018c; Eurostat, 2018b, 2018c, 2018e, 2018f.

Figure 2.3 **Development in EU-28 emissions from main source sectors of As, Cd, Ni, Pb, Hg and BaP, 2000-2016 (% of 2000 levels)**



Notes: Only pollutants for which the sector contributes more than 5 % to the total pollutant emissions are shown in the figures. The emissions reported from Portugal for the activity 'asphalt blowing in refineries' (under the industrial processes and product use sector) were not taken into account to ensure consistency between nationally reported data (they were not reported by any other country).

Source: EEA, 2018e.

Box 2.1 Choice of sectoral activity data

Sectoral activity data to be compared with the change in emissions over time were chosen as follows:

For road and non-road transport sectors, sectoral activity is expressed in terms of passenger and freight transport volume (described in original units of billion passenger-kilometres (pkm) and billion tonne-kilometres (tkm)) per year for road transport (cars, motorbikes, buses and coaches) and for non-road transport (railways, trams, metro, air and sea) (European Commission, 2018c). One pkm or tkm represents the transport of one passenger or tonne of goods, respectively, by a defined mode of transport over 1 km. The figures include intra-EU air and sea transport but not transport activities between the EU and the rest of the world. Together, the volume of passengers and freight transported give a measure of activity for the total transport sector.

For the commercial, institutional and household sector and the energy use in industry sector, sectoral activity is expressed in terms of the approximate final energy consumption (described in original units of e.g. tonnes of oil equivalent, TOE) (Eurostat, 2018e). Final energy consumption was chosen as a proxy for sectoral activity, since it is the total amount of energy consumed by the end users from all energy sources, i.e. it is the energy that reaches the final consumer's door, excluding energy used by the energy sector itself.

For the energy production and distribution sector, sectoral activity is expressed in terms of both total primary energy production (Eurostat, 2018e) and total gross electricity production (Eurostat, 2018f), described in original units of, for example, TOE. The production of primary energy is the extraction of energy products, in any useable form, from natural sources. Secondary energy (e.g. electricity) is a carrier of energy and is produced by converting primary sources of energy. Total gross electricity generation covers gross electricity generation in all types of power plants, and at plant level it is defined as the electricity measured at the outlet of the main transformers. The production of primary and secondary energy (of which electricity was used here as an example) together provides a measure of the energy production and distribution sector activity.

For the agriculture sector, and the industrial processes and product use sector, sectoral activity is expressed in terms of gross value added (GVA) (Eurostat, 2018c) and described in the original units of euros ([12]). GVA is a measure of the value of goods and services produced in a sector, and was thus used as a proxy for activity in these production-based sectors.

For the waste sector, sectoral activity is expressed by the total mass of waste generated (Eurostat, 2018b) and described in the original units of tonnes. This includes both hazardous and non-hazardous waste from all classified economic activities plus households, giving an indication of the total activity in the waste sector.

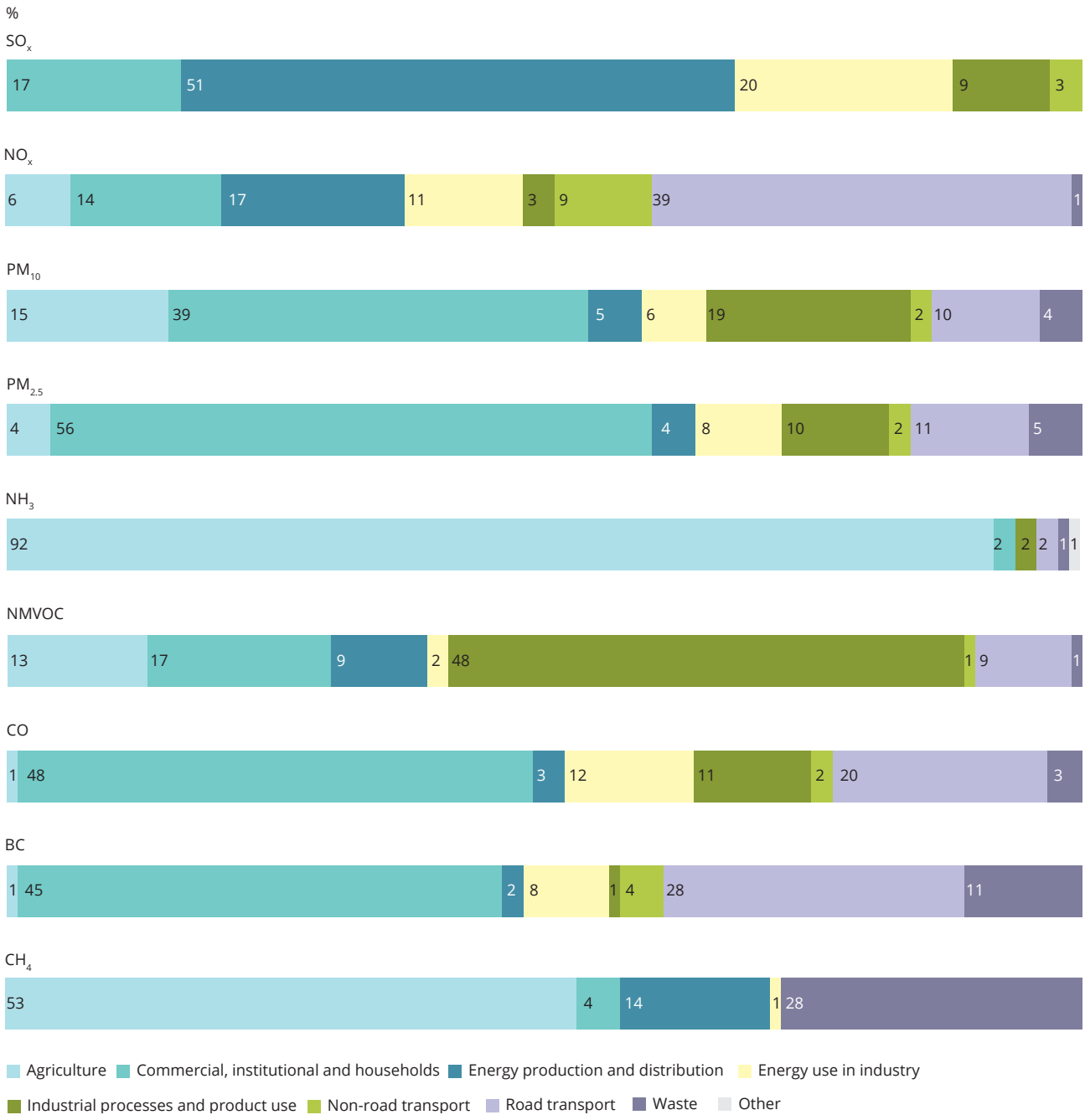
and energy sectors have also been targeted by EU legislation (EEA, 2017b, 2018i). Emission limits have been put in place for combustion plants (e.g. Directive (EU) 2015/2193 on medium combustion plants). Principles have also been outlined regarding permits and the control of installations based on an integrated approach and applying best available techniques (BAT) (e.g. Directive 2010/75/EU on industrial emissions).

Although a decoupling of some pollutant emissions from sectoral activities is indicated in both the waste sector and the commercial, institutional and households sector, other pollutants in these sectors show no (or limited) decoupling; the same is true for the agriculture sector. For example, in the waste sector, CH_4 emissions have declined significantly, whereas $PM_{2.5}$ and BC emissions (along with the quantity of total waste produced) have remained relatively constant. This decoupling of CH_4 emissions may be due to changes in the way waste is managed (e.g. a reduction in landfilling) combined with specific standards to mitigate CH_4 (e.g. reducing landfill CH_4 emissions by capture/combustion of landfill gas), with a variety of surrounding EU waste targets in place.

Figures 2.4 and 2.5 give an overview of each sector's contribution to total emissions for all chosen pollutants in the EU28, for 2016. The **road transport** sector was the largest contributor to total NO_x emissions and a significant contributor of BC, CO, primary $PM_{2.5}$ and Pb emissions. **Energy production and distribution** was the largest contributor to SO_x, Hg and Ni, as well as a significant contributor of NO_x, As and CH_4 emissions. **Agriculture** contributed

([12]) See previous footnote ([10]).

Figure 2.4 **Contribution to EU-28 emissions from main source sectors in 2016 of SO_x, NO_x, primary PM_{10}, primary $PM_{2.5}$, NH_3, NMVOCs, CO, BC and CH_4**

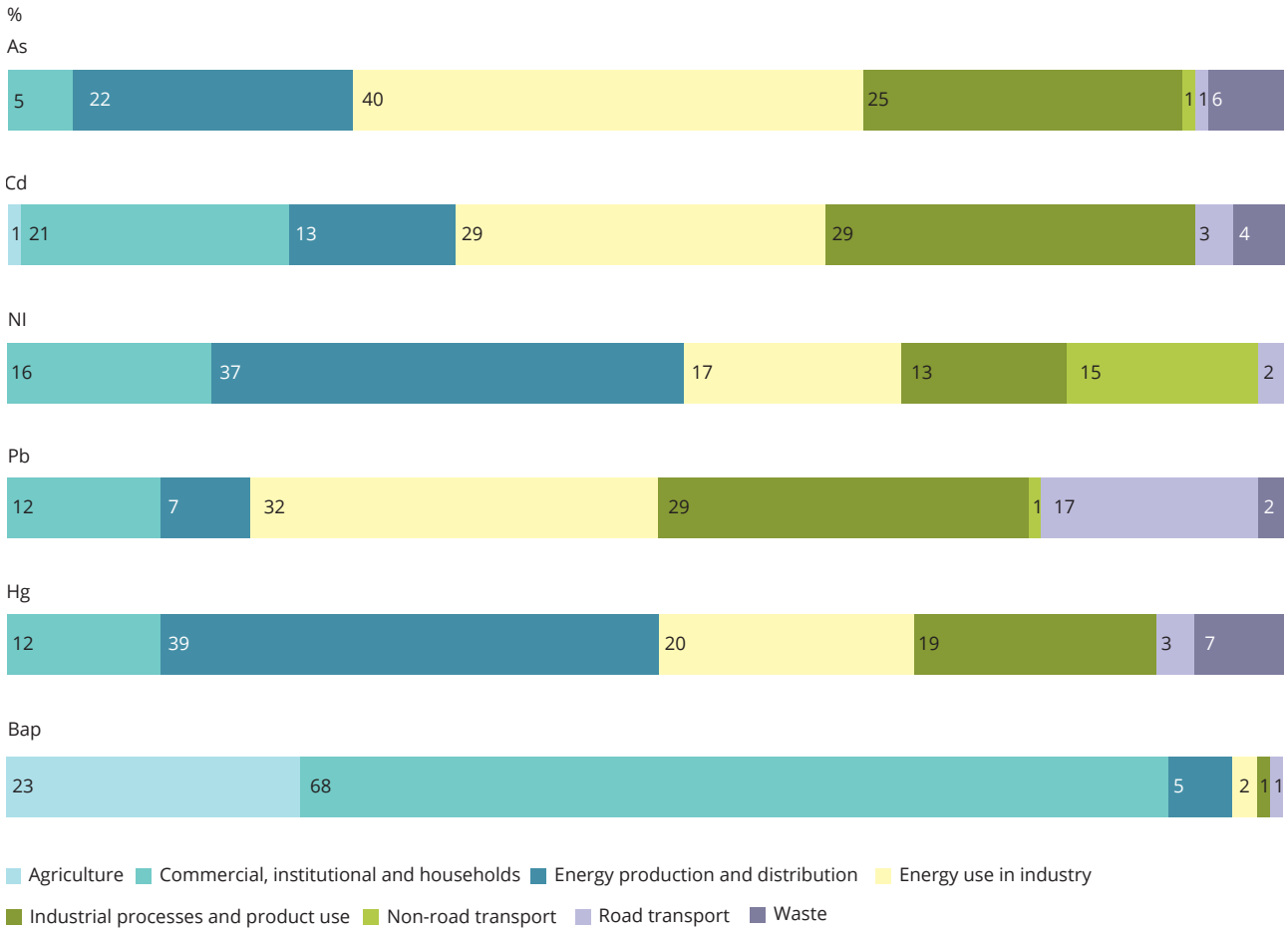


Sources: EEA, 2018c, 2018e.

the majority of NH_3 and CH_4, as well as a significant amount of BaP, primary PM_{10} and NMVOC emissions. The **commercial, institutional and households sector** was the largest contributor to BaP, total primary PM_{10} and $PM_{2.5}$, CO and BC and also contributed to NMVOC, Cd, SO_x, Ni and NO_x emissions. **Industrial processes and product use** ([13]) contributed the majority of NMVOC emissions and a significant amount of primary PM, As, Cd, Pb and Hg emissions. **Energy use in industry** contributed the majority of As, Pb and Cd emissions and a significant amount of SO_x, Hg, Ni and CO emissions. **Waste** contributed a significant amount of CH_4 emissions and also BC. These trends are similar for the EEA-33 countries. Some of the largest distribution differences were for primary PM_{10}, SO_x and CH_4 emissions. The largest difference between

([13]) See previous footnote ([7]).

Figure 2.5 **Contribution to EU-28 emissions from main source sectors in 2016 of As, Cd, Ni, Pb, Hg and BaP**



Source: EEA, 2018e.

Note: The emissions reported from Portugal for the activity 'asphalt blowing in refineries' (under the industrial processes and product use sector) were not taken into account to ensure consistency between nationally reported data (they were not reported by any other country).

the EU-28 and EEA-33 was the primary PM_{10} emissions from the industrial processes and product use sector, which accounted for 31 % of the total PM_{10} in 2016 in the EEA-33, but only 19 % of the total PM_{10} in the EU-28. This is because Turkey contributed to more than half of the PM_{10} emissions from that sector.

Finally, the contributions from the different emission source sectors to ambient air pollutant concentrations and air pollution impacts depend not only on the amount of pollutant emitted, but also on the proximity to the source, emission/dispersion conditions and other factors, such as topography. Emission sectors with low emission heights, such as traffic and household emissions, generally make larger contributions to surface concentrations and health impacts in urban areas than emissions from high stacks.

3 Particulate matter

3.1 European air quality standards and World Health Organization guidelines for particulate matter

The legal standards set by the Ambient Air Quality Directive (EU, 2008) for both PM_{10} and $PM_{2.5}$ can be found in Table 1.1. and the AQGs set by the WHO in Table 1.3.

3.2 Status of concentrations

The EEA received PM_{10} data for 2016, with sufficient valid measurements (a minimum coverage of 75%) from around 2 900 stations located in all the EEA-39 countries (except Liechtenstein) and Andorra.

PM_{10} concentrations continued to be above the EU daily limit value in large parts of Europe in 2016 (27 countries). Map 3.1 shows concentrations of PM_{10} in relation to the daily limit value. 19 % of stations reported concentrations of PM_{10} above this daily limit value in 19 Member States and eight other reporting countries (see Figure 3.1). 97 % of those stations were either urban (87 %) or suburban (10 %). Some of these high daily mean PM_{10} levels were observed during high PM_{10} pollution episodes in the winter, spring and autumn of 2016, as explained in Box 3.1.

Concentrations above the PM_{10} annual limit value (40 µg/m^3) in 2016 were monitored in 6 % of all the reporting stations. 92% of these stations were located in Turkey (116), Poland (29), the former Yugoslav Republic of Macedonia (13) and Bulgaria (11) ([14]). The stricter value of the WHO AQG for PM_{10} annual mean (20 µg/m^3) was exceeded at 48 % of the stations and in all the reporting countries, except Estonia, Iceland, Ireland and Switzerland (see Map 3.2 and Figure 3.2).

Regarding $PM_{2.5}$, data with a minimum coverage of 75 % of valid data were received from 1 327 stations located in all the EEA-39 countries, except Liechtenstein and Montenegro.

In 2016, the $PM_{2.5}$ concentrations were higher than the annual limit value in four Member States and four other reporting countries (see Figure 3.3 and Map 3.3). These values above the limit value were registered in around 5 % of all the reporting stations and also occurred primarily (97 % of cases) in urban or suburban areas.

The WHO guideline for $PM_{2.5}$ annual mean (10 µg/m^3) was exceeded at 68 % of the stations, located in 32 of the 37 countries reporting $PM_{2.5}$ data (see Figure 3.3 and Map 3.3). Estonia, Finland, Hungary, Norway and Switzerland did not report any exceedances of the WHO AQG for $PM_{2.5}$.

The rural background concentration levels of PM vary across Europe. In 2016, concentrations above the PM_{10} daily limit value occurred in several rural background stations across Italy (nine), Czechia (three), Turkey (two) and Slovenia (one). There was also one rural background station in Turkey, whose 2016 annual mean concentration exceeded the PM_{10} annual limit value. With regard to $PM_{2.5}$, two rural background stations in Czechia registered concentrations above the annual limit value.

The Ambient Air Quality Directive (EU, 2008) also requires Member States to make additional measurements on the chemical speciation concentrations of fine particulate matter, at least at one rural background station. The chemical species that have to be measured are SO_4^{2-}, NO_3^-, sodium (Na^+), potassium (K^+), NH_4^+, chloride (Cl^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), elemental carbon (EC) and organic carbon (OC).

In 2016, the countries that reported these species were Austria, Croatia, Cyprus, Denmark, Finland (except EC), Germany, Ireland, Latvia (except EC

([14]) There was also at least one station with values above the PM_{10} annual limit value in the Member States of Croatia (one), France (two), Greece (two), Italy (two), Malta (one) and Spain (one) and in the cooperating countries of Bosnia and Herzegovina (three) and Montenegro (one) (see Map 3.2).

Box 3.1 $PM_{2.5}$ and PM_{10} pollution episodes in 2016

Several large-scale PM pollution events affected European air quality in the winter, spring and autumn of 2016. Throughout the year, the Copernicus Atmosphere Monitoring Service (CAMS) (2017) identified two major PM_{10} pollution events during the winter (1-9 January and 17-24 December) and three major $PM_{2.5}$ pollution events during the spring (9-20 March), autumn (24-28 October) and winter (4-9 December).

Stagnant dry conditions combined with higher primary PM emissions from residential combustion often lead to events with high PM concentrations over Europe during winter, which can affect large areas and persist for several days. The January PM_{10} episode (1-9 January) led to a high number of stations measuring daily mean concentrations above 50 µg/m³ across central Europe and, to a lesser extent, across western and northern Europe.

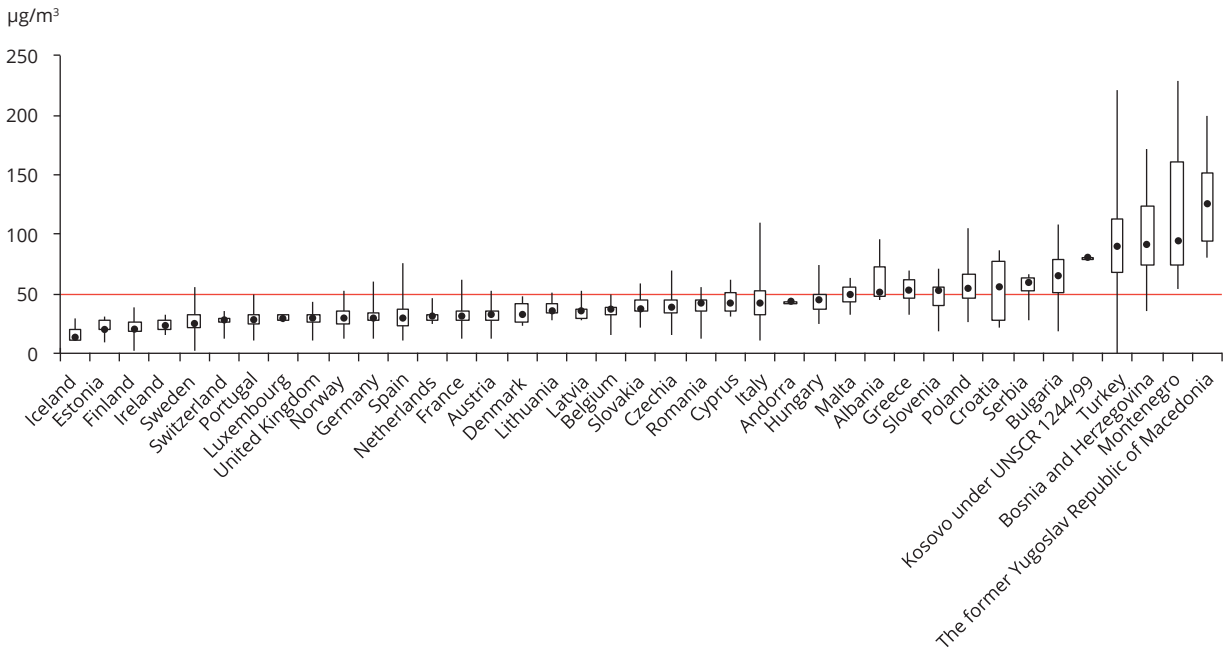
The March $PM_{2.5}$ episode (9- 20 March) was substantial and led to daily mean concentrations exceeding the WHO guideline of 25 µg/m³ in many monitoring stations throughout central, western and northern Europe. CAMS's (2017) evaluation of the contribution of anthropogenic emission sources to this episode showed that agricultural NH_3 emissions were the most significant cause of the high $PM_{2.5}$ pollution levels, and that this contribution was particularly large across western, central and eastern Europe. Residential combustion (in central Europe), industrial emissions (in western Europe) and a dust intrusion in both eastern and central Europe also contributed to the episode.

The October $PM_{2.5}$ episode (24-28 October) occurred across central, western and northern Europe. CAMS (2017) associated the elevated levels of $PM_{2.5}$ in the United Kingdom, France and central Europe primarily with NH_3 emissions from agriculture (only minor contributions from other sectors) and identified an intrusion of Saharan desert dust in Spain and Portugal during the same period.

Lastly, a major December $PM_{2.5}$ episode (4-9 December) occurred across many areas of Europe. CAMS's (2017) evaluation again indicates that agricultural NH_3 emissions made significant contributions in different areas of western and central Europe, while residential combustion made very large contributions in central and southern Europe (and also France (LCSQA, 2017)). There were also moderate contributions from traffic emissions across most of continental Europe.

The December PM_{10} pollution episode (17-24 December) affected central, western and northern Europe. Anthropogenic emission sources contributed largely to the high PM_{10} concentrations across western and central Europe, with a significant contribution from residential combustion in central and southern Europe (CAMS, 2017), and also in France (LCSQA, 2017).

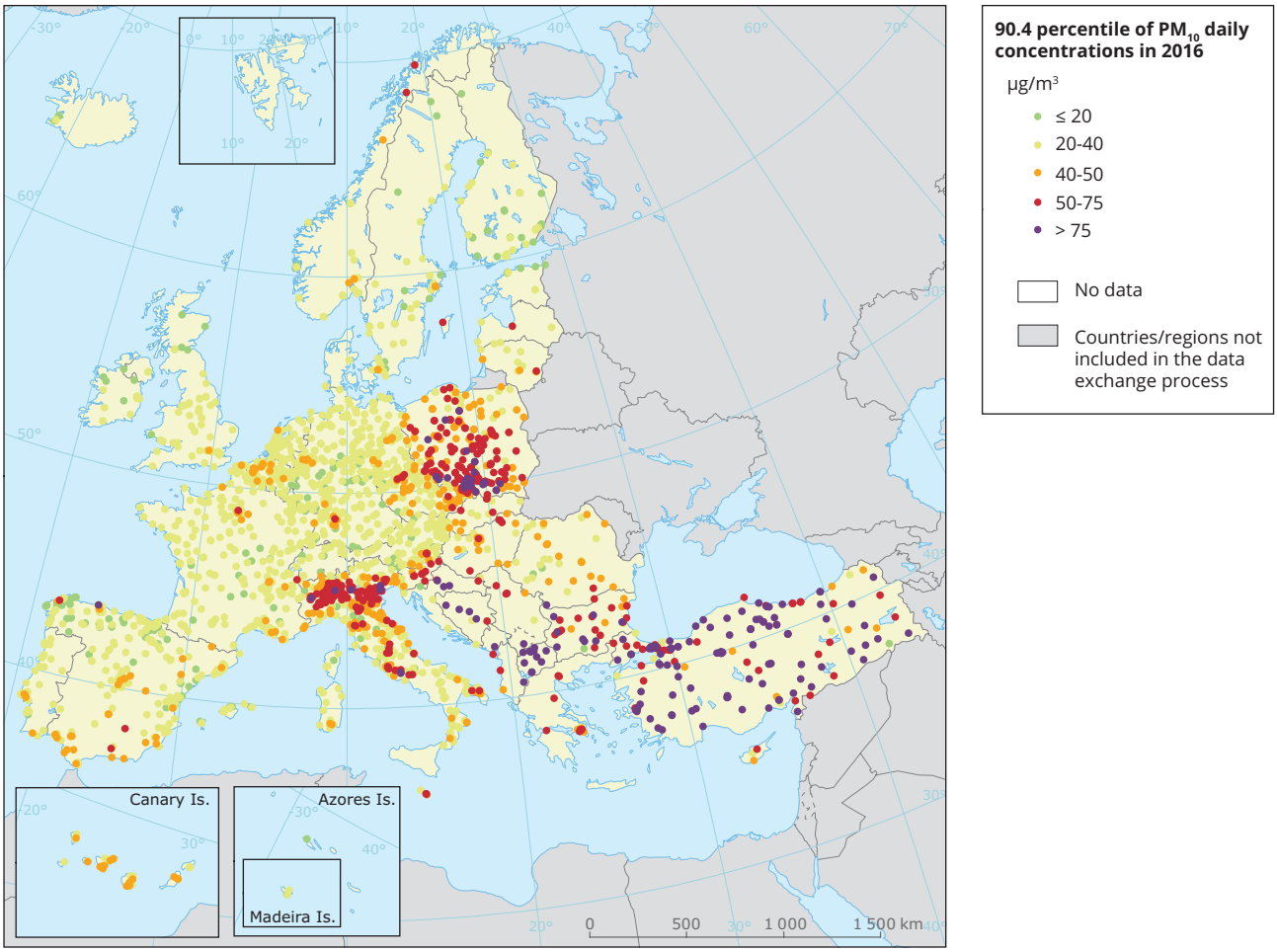
Figure 3.1 PM_{10} concentrations in relation to the daily limit value in 2016



Notes: The graph is based, for each country, on the 90.4 percentile of daily mean concentration values corresponding to the 36th highest daily mean. For each country, the lowest, highest and median 90.4 percentile values (in µg/m³) recorded at its stations are given. The rectangles mark the 25th and 75th percentiles. At 25 % of the stations, levels are below the lower percentile; at 25 % of the stations, concentrations are above the upper percentile. The daily limit value set by EU legislation is marked by the horizontal line. The graph should be read in relation to Map 3.1, as the country situation depends on the number of stations considered.

Source: EEA, 2018a.

Map 3.1 Concentrations of PM_{10}, 2016 — daily limit value



Notes: Observed concentrations of PM_{10} in 2016. The possibility of subtracting contributions to the measured concentrations from natural sources and winter road sanding/salting has not been considered. The map shows the 90.4 percentile of the PM_{10} daily mean concentrations, representing the 36th highest value in a complete series. It is related to the PM_{10} daily limit value, allowing 35 exceedances of the 50 µg/m³ threshold over 1 year. Dots in the last two colour categories indicate stations with concentrations above this daily limit value. Only stations with more than 75 % of valid data have been included in the map. The French overseas territories' stations are not shown in the map but can be found at https://www.eea.europa.eu/data-and-maps/dashboards/air-quality-statistics.

Source: EEA, 2018a.

and OC), Lithuania, Malta, the Netherlands, Poland, Portugal (except NO_3^-), Slovenia, Spain and the United Kingdom. Values can be found at https://www.eea.europa.eu/data-and-maps/dashboards/air-quality-statistics-expert-viewer (accessed 17 July 2018) and they range between the following minima and maxima:

- sulphate, between 0.18 and 3.08 µg/m³,
- nitrate, between 0.018 and 3.090 µg/m³,
- sodium, between 0.027 and 0.610 µg/m³,
- potassium, between 0.0091 and 0.3266 µg/m³,
- ammonium, between 0.011 and 1.973 µg/m³,
- chloride, between 0.0060 and 1.2150 µg/m³,
- calcium, between 0.0035 and 0.1650 µg/m³,
- magnesium, between 0.0027 and 0.1490 µg/m³,
- elemental carbon, between 0.075 and 2.319 µg/m³,
- organic carbon, between 0.44 and 14.71 µg/m³.

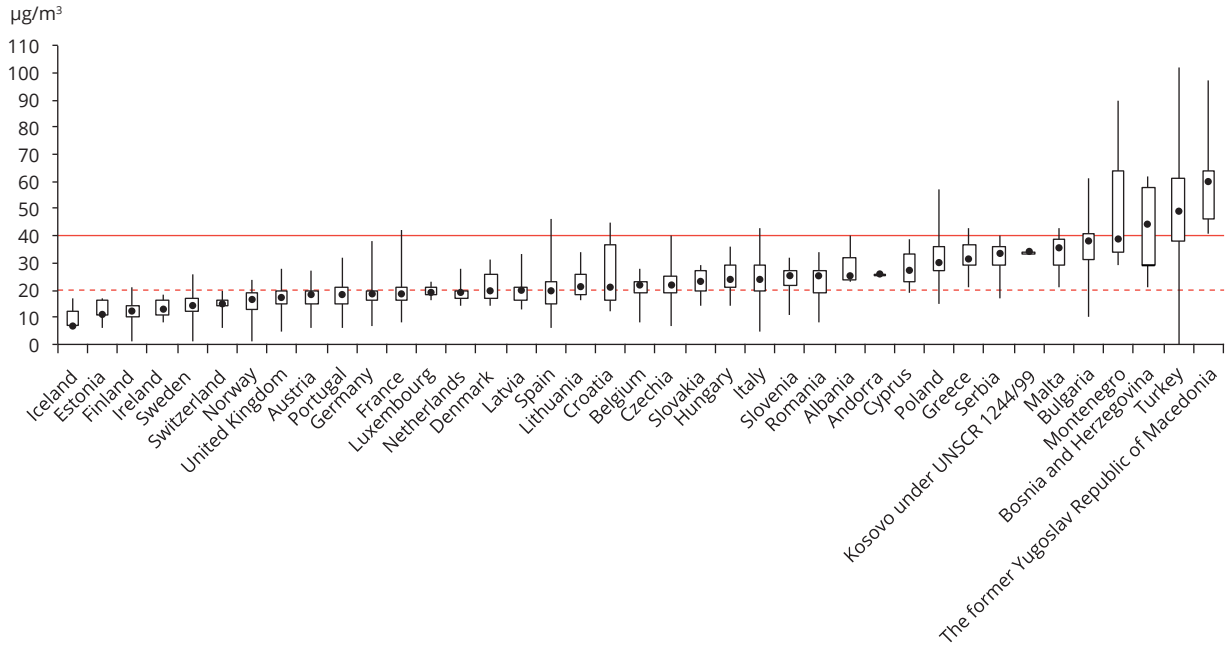
3.3 $PM_{2.5}$ average exposure indicator

The Ambient Air Quality Directive (EU, 2008) also sets two additional targets for $PM_{2.5}$, the exposure concentration obligation (ECO) and the national exposure reduction target (NERT) (see Table 1.1). Both targets are based on the average exposure indicator (AEI), calculated at national level. The AEI is an average of concentration levels (over a 3-year period) measured at urban background stations (representative of general urban population exposure) selected for this purpose by every national authority. The reference year for the AEI is 2010 (average 2008-2010), but the Ambient Air Quality Directive offered two additional alternatives where data are not available for 2008: (1) the AEI 2010, which refers to a 2-year average (2009 and 2010) instead of the 3-year average; or (2) the AEI 2011 (the average from 2009 to 2011). For comparability purposes, the data presented here are analysed with reference to the AEI 2011, independently of the reference year chosen by each Member State. The exception is Croatia for which 2015 is the AEI reference year.

Figure 3.4 shows the AEI for every EU-28 Member State calculated for 2016 (average 2014-2016) and the situation in relation to the ECO. The bars show the AEI 2016 using the stations designated for this purpose by the Member States ([15]), while the dots show instead the 3-year (2014-2016) average concentrations from measurements at all urban and suburban background stations with 75 % data coverage. This calculation, covering the urban and suburban background stations, has been used in previous *Air quality in Europe* reports as an approximation of the AEI and is presented here for comparison with the information presented in those reports. This year, for the very first time, we also include the calculation for the rest of the non-EU countries using their reported urban and suburban background stations.

For the 27 countries where the AEI could be calculated using the designated stations, the AEI 2016 was above the exposure concentration obligation in Slovakia (21 µg/m³ for the AEI 2015 (average 2014-2015), since Slovakia did not designate AEI stations in 2013 or 2016 ([16])), Poland (23 µg/m³) and Bulgaria (25 µg/m³).

Figure 3.2 PM_{10} concentrations in relation to the annual limit value in 2016



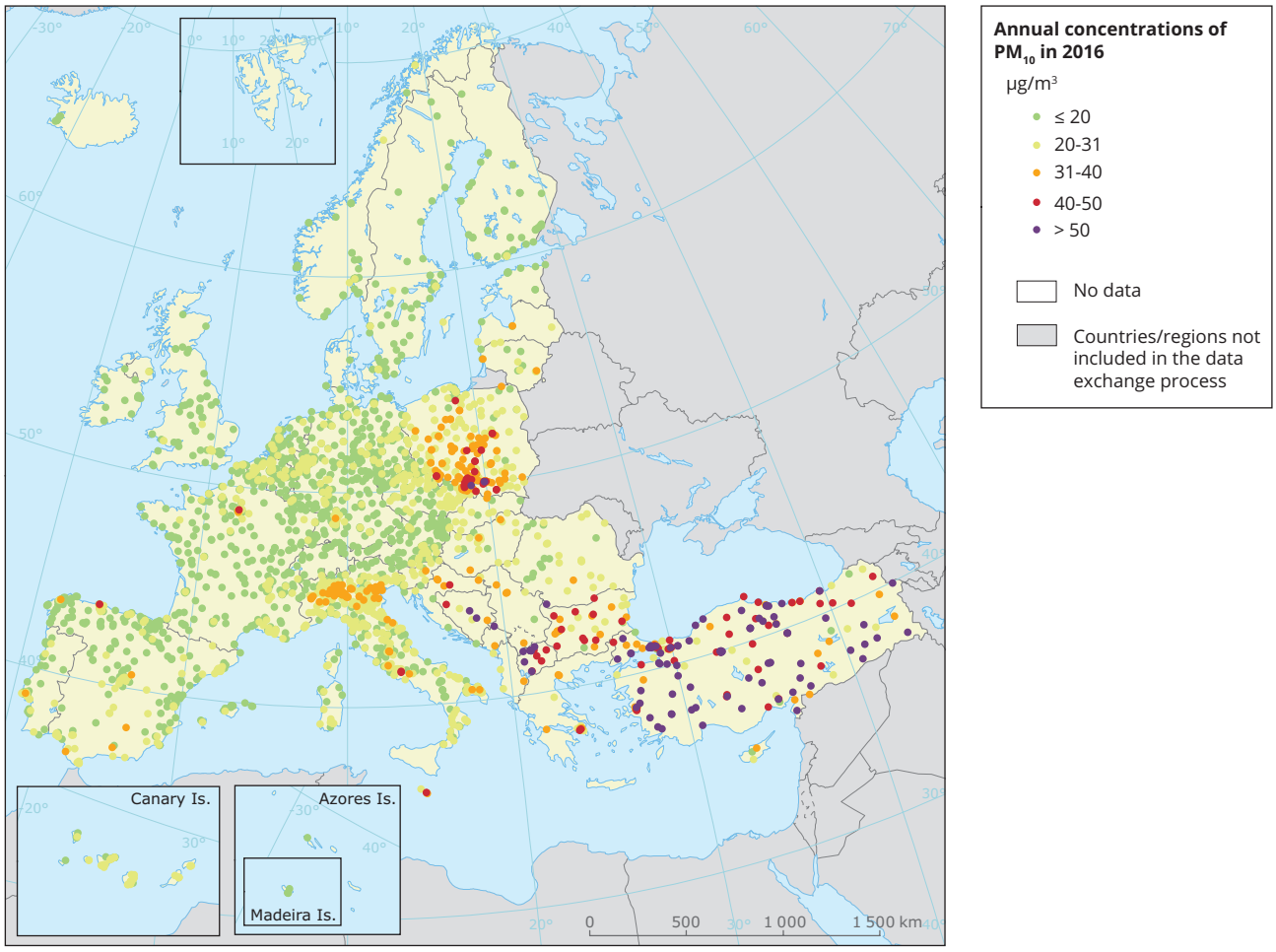
Notes: The graph is based on annual mean concentration values. For each country, the lowest, highest and median values (in µg/m³) recorded at its stations are given. The rectangles mark the 25th and 75th percentiles. At 25 % of the stations, levels are below the lower percentile; at 25 % of the stations, concentrations are above the upper percentile. The annual limit value set by EU legislation is marked by the upper continuous horizontal line. The WHO AQG is marked by the lower dashed horizontal line. The graph should be read in relation to Map 3.2, as the country situation depends on the number of stations considered.

Source: EEA, 2018a.

([15]) No AEI stations designed by Croatia and Greece. The non-EU country of Norway has also designated AEI stations. The rest of countries covered by this report where the EU Directives do not apply are not obliged to designate AEI stations.

([16]) However, taking into account all the urban and suburban stations results in a value of 18 µg/m³ for 2016.

Map 3.2 Concentrations of PM_{10}, 2016 — annual limit value



Notes: Observed concentrations of PM_{10} in 2016. The possibility of subtracting contributions to the measured concentrations from natural sources and winter road sanding/salting has not been considered. Dots in the last two colour categories indicate stations reporting concentrations above the EU annual limit value (40 µg/m³). Dots in the first colour category indicate stations reporting values below the WHO AQG for PM_{10} (20 µg/m³). Only stations with more than 75 % of valid data have been included in the map. The French overseas territories' stations are not shown in the map but can be found at https://www.eea.europa.eu/data-and-maps/dashboards/air-quality-statistics.

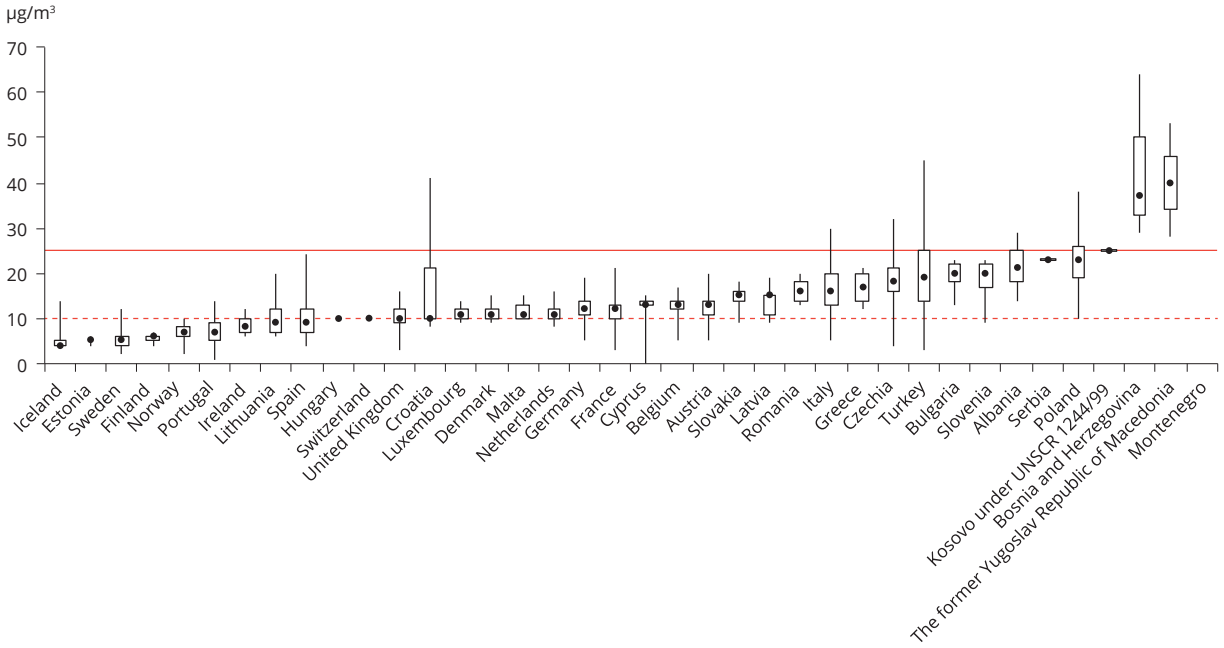
Source: EEA, 2018a.

Furthermore, based on the average of $PM_{2.5}$ concentrations measured at urban and suburban background stations, Croatia was also above the exposure concentration obligation with an estimated AEI 2016 of 21 µg/m³. Other countries with an estimated AEI above 20 µg/m³ are Serbia (23 µg/m³, only data for 2016), Albania (25 µg/m³, 2015-2016), Kosovo under UNSCR 1244/99 (27 µg/m³, 2015-2016), Bosnia and Herzegovina (33 µg/m³, 2016), and the Former Yugoslav Republic of Macedonia (52 µg/m³, 2015-2016).

Figure 3.5 shows the situation of the EU Member States and Norway in relation to the NERT. This reduction target is expressed as a percentage of the initial AEI 2010 (here, as stated above, AEI 2011 has been used for comparison). The dots indicate the percentage reduction to be attained in AEI 2020 (average 2018-2020) and the bars indicate the reduction in the AEI 2016 (AEI 2014 for Hungary and AEI 2015 for Slovakia) as a percentage of the AEI 2011 (AEI 2015 for Croatia). It demonstrates that more than half of the 29 countries considered ([17]) have already attained the corresponding NERT values.

([17]) Austria, Belgium, Cyprus, Denmark, Estonia, Finland, France, Germany, Ireland, Lithuania, Luxembourg, the Netherlands, Norway, Sweden and the United Kingdom.

Figure 3.3 $PM_{2.5}$ concentrations in relation to the annual limit value in 2016



Notes: The graph is based on annual mean concentration values. For each country, the lowest, highest and median values (in µg/m³) recorded at its stations are given. The rectangles mark the 25th and 75th percentiles. At 25 % of the stations, levels are below the lower percentile; at 25 % of the stations, concentrations are above the upper percentile. The limit value set by EU legislation is marked by the upper continuous horizontal line. The WHO AQG is marked by the lower dashed horizontal line. The graph should be read in relation to Map 3.3, as the country situation depends on the number of stations considered.

Source: EEA, 2018a.

3.4 Contribution of PM precursor emissions, natural sources, climate change and meteorological variability to ambient PM concentrations

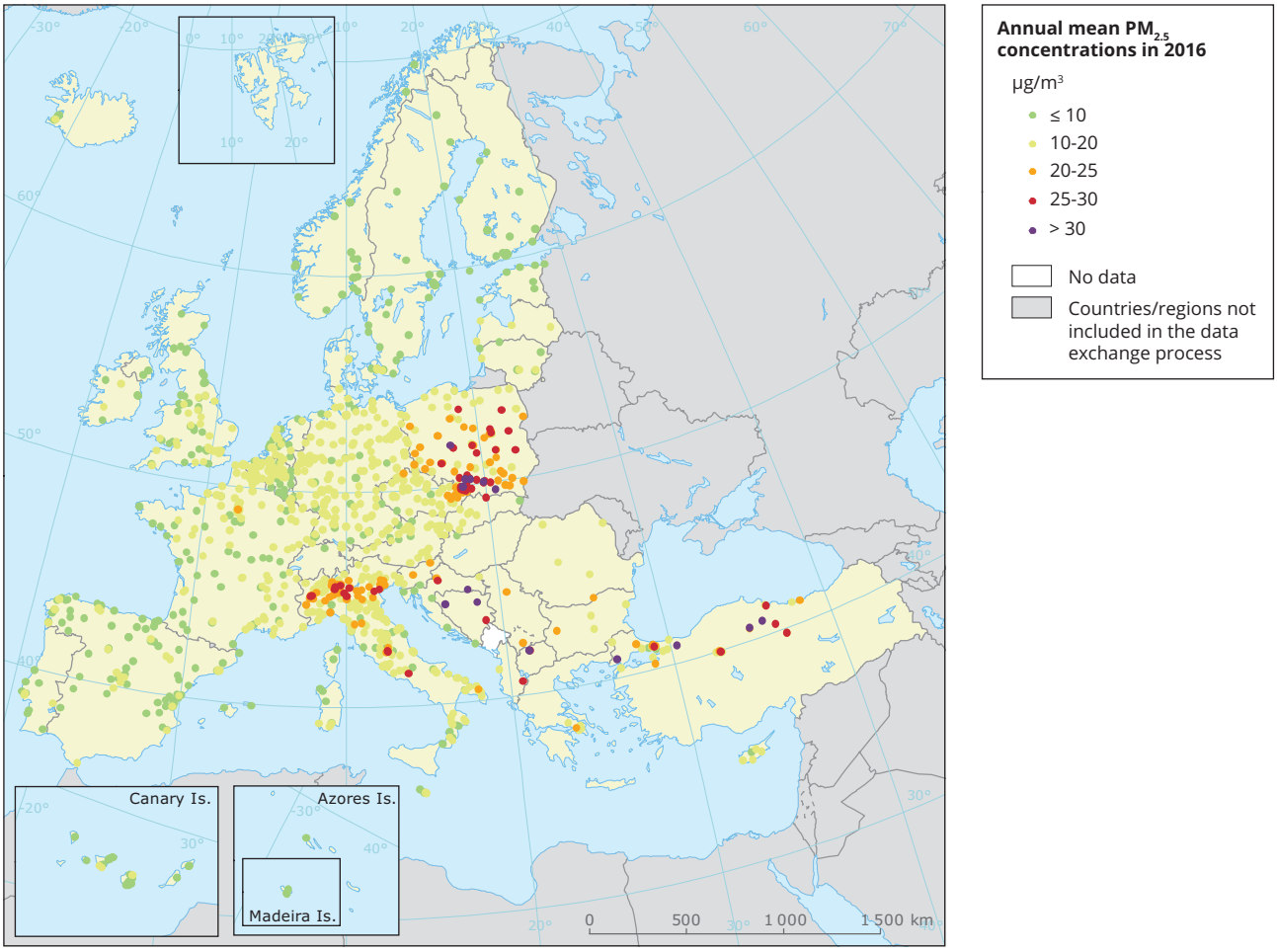
With the exception of NH_3, the reductions in emissions of the secondary PM precursors (NO_x, SO_x and NMVOCs) were much larger than the reductions in primary PM emissions from 2000 to 2016 in the EU-28 (see Figure 2.1). Regarding secondary PM, a reduction in sulphur emissions has contributed to a shift in PM composition from $(NH_4)_2SO_4$ to NH_4NO_3; therefore, reductions in emissions are not directly transferred to falls in concentrations (EMEP, 2016). The EuroDelta-Trends modelling experiment (ETC/ACM, 2017c) estimated that the impact of the reduction of European emissions of PM precursors and of primary PM was the most important factor in explaining the reduction in PM_{10} concentrations between 1990 and 2010 in Europe. In the 1990s, meteorological conditions had an impact on the trends similar to that of European emission changes for the Iberian Peninsula and to some extent for France.

The modelled attribution for each aerosol compound contributing to the PM_{10} mix showed that European anthropogenic emission changes also dominated the evolution of secondary PM and secondary organic aerosols, contributing in all cases to a decrease in the concentrations of those compounds.

In terms of urban background $PM_{2.5}$, it has been shown that in southern Europe 65-70 % of the concentration arises from secondary aerosols, whereas only 30-35 % is attributed to primary aerosols (Amato et al., 2016). This reinforces the fact that both PM gaseous precursors and primary PM should be abated to reduce PM pollution.

Natural sources, which are not targeted by mitigation measures, contribute to both background PM concentrations and episodes with high PM levels, e.g. as a result of desert dust transport and wildfires. Current efforts to reduce anthropogenic emissions of primary PM

Map 3.3 Concentrations of $PM_{2.5}$, 2016 — annual limit value

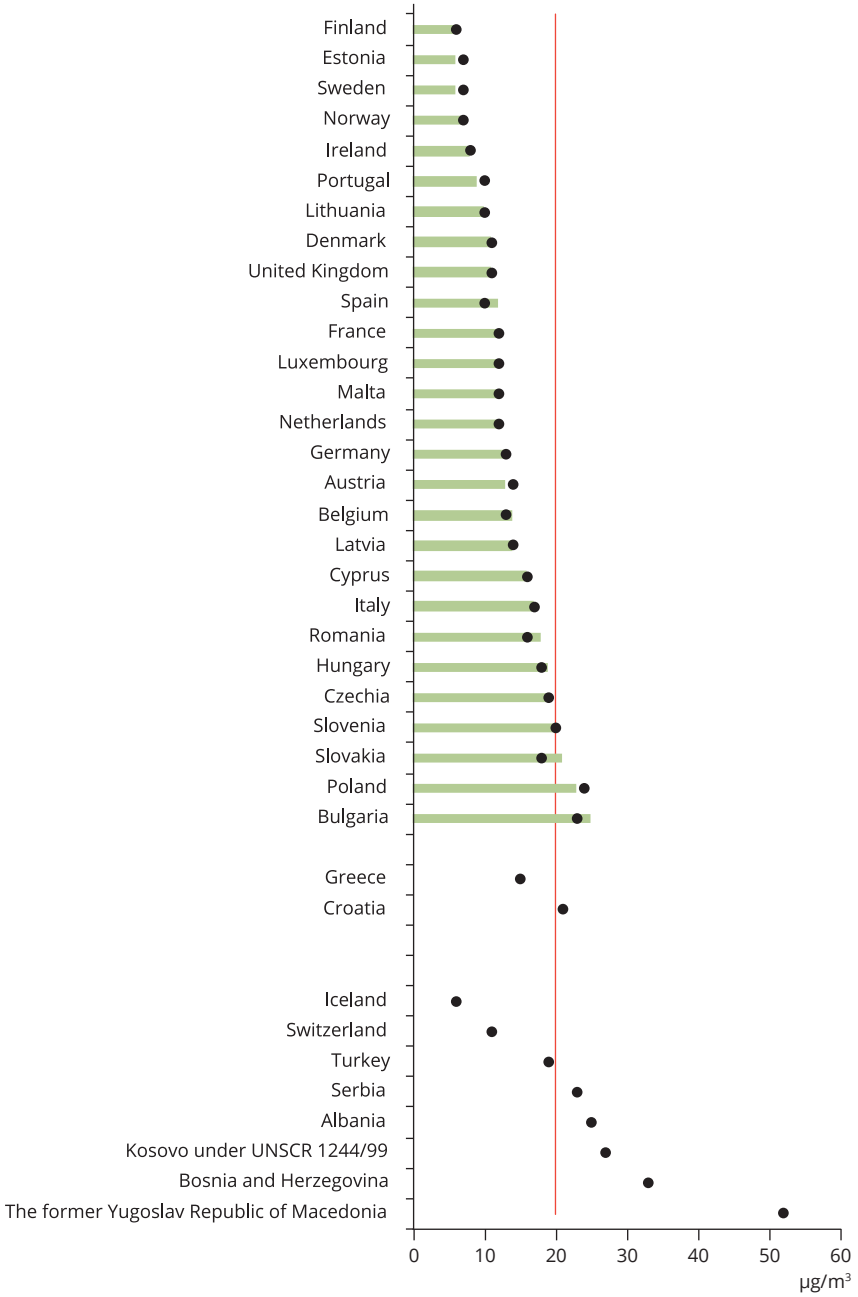


Notes: Observed concentrations of $PM_{2.5}$ in 2016. The possibility of subtracting contributions to the measured concentrations from natural sources and winter road sanding/salting has not been considered. Dots in the last two colour categories indicate stations reporting concentrations above the EU annual limit value (25 µg/m³). Dots in the first colour category indicate stations reporting values below the WHO AQG for $PM_{2.5}$ (10 µg/m³). Only stations with more than 75 % of valid data have been included in the map. The French overseas territories' stations are not shown in the map but can be found at https://www.eea.europa.eu/data-and-maps/dashboards/air-quality-statistics

Source: EEA, 2018a.

and PM precursors will lead to an increase in the relative importance of natural emission sources. With regard to the African dust outbreaks, there is a small body of evidence that indicates an increase in mortality and morbidity during these pollution episodes, and that also suggests that PM has a larger health impact during dust episodes (Pérez et al., 2012; Stafoggia et al., 2016). Causes are still not well defined, but it is probably because there are large accumulations of pollution locally during dust episodes, following a thinning of the planetary boundary layer. This being the case, measures to abate local emissions and to alert the most susceptible populations could be effective during dust outbreaks. Wildfires are a significant cause of air pollutants (Langmann, 2009; van der Werf et al., 2010; Granier et al., 2011; Kaiser et al., 2012), sometimes affecting air quality far from its source (Forster et al., 2001; Stohl et al., 2006; Eckhardt et al., 2007). Wildfire occurrence and severity seem to have increased in recent decades and the increase is predicted to continue as a result of climate change (Knorr et al., 2017). Knorr et al. (2017) estimated that in the future (scenarios for 2090) wildfire PM emissions may approach or exceed anthropogenic emissions, even in densely populated areas in the eastern Europe-Russia-central Asia region. It is therefore necessary to develop and implement effective methods for wildfire management and prevention.

Figure 3.4 Average Exposure Indicator in 2016 and exposure concentration obligation



Notes: The bars show the average exposure indicator (AEI) calculated in 2016 (averages 2014-2016) using the stations designated for this purpose by the Member States (except for Croatia and Greece, where no stations have been designated) and Norway.

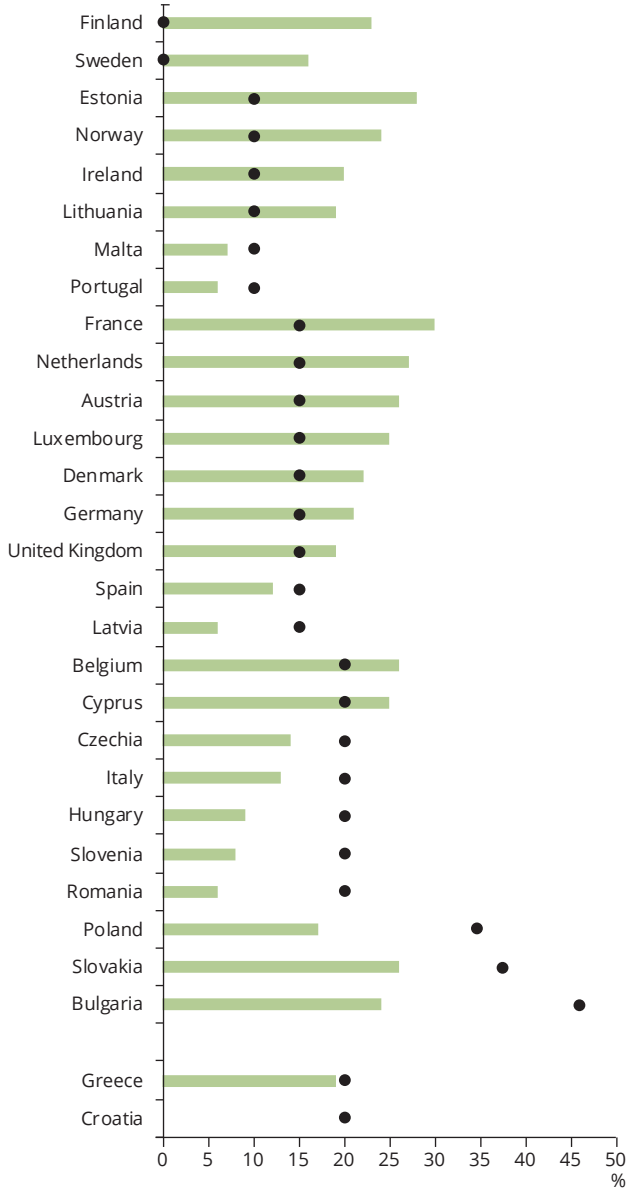
The dots show all urban and suburban background $PM_{2.5}$ concentrations (for stations with at least 75 % of data coverage) in all reporting countries presented as 3-year (2014-2016) averages, as an approximation of the AEI in 2016 and to facilitate comparison with information provided in previous Air quality in Europe reports.

The vertical line represents the exposure concentration obligation for the EU-28, set at 20 µg/m³, to be reached by 2015.

For Hungary, which did not designate AEI stations nor report $PM_{2.5}$ data from urban or suburban background stations in 2015 or 2016, the AEI and the estimation using urban background stations are presented for 2014 (average 2012-2014). For Slovakia, which did not designate AEI stations in 2013 or 2016, the AEI 2015 (average 2014-2015) is presented. For Greece, Albania, Iceland, Kosovo, Switzerland and the former Yugoslav Republic of Macedonia, the estimation using urban background stations only considered the years 2015 and 2016. For Bosnia and Herzegovina, Serbia and Turkey, it considered only the last.

Source: EEA, 2018a.

Figure 3.5 **Percentage of reduction of AEI 2016 in relation to AEI 2011 and distance to the national exposure reduction target**



Notes: Bars indicate the reduction of the AEI 2016 as a percentage of the AEI 2011 (AEI 2015 in the case of Croatia, see main text). Dots indicate the reduction to be obtained in the AEI 2020 as a percentage of the AEI 2011 (AEI 2015 in the case of Croatia). If the end of the bar is to the right of the dot, the NERT has already been reached in 2016.

For Croatia and Greece, where no stations have been designated for the AEI calculation, all urban and suburban background stations have been used instead.

For Hungary, which did not designate AEI stations or report $PM_{2.5}$ data from urban background stations in 2015 nor 2016, the reduction of the AEI 2014 (average 2012-2014) is presented. For Slovakia, which did not designate AEI stations in 2013 nor 2016, the reduction of the AEI 2015 (average 2014-2015) is presented.

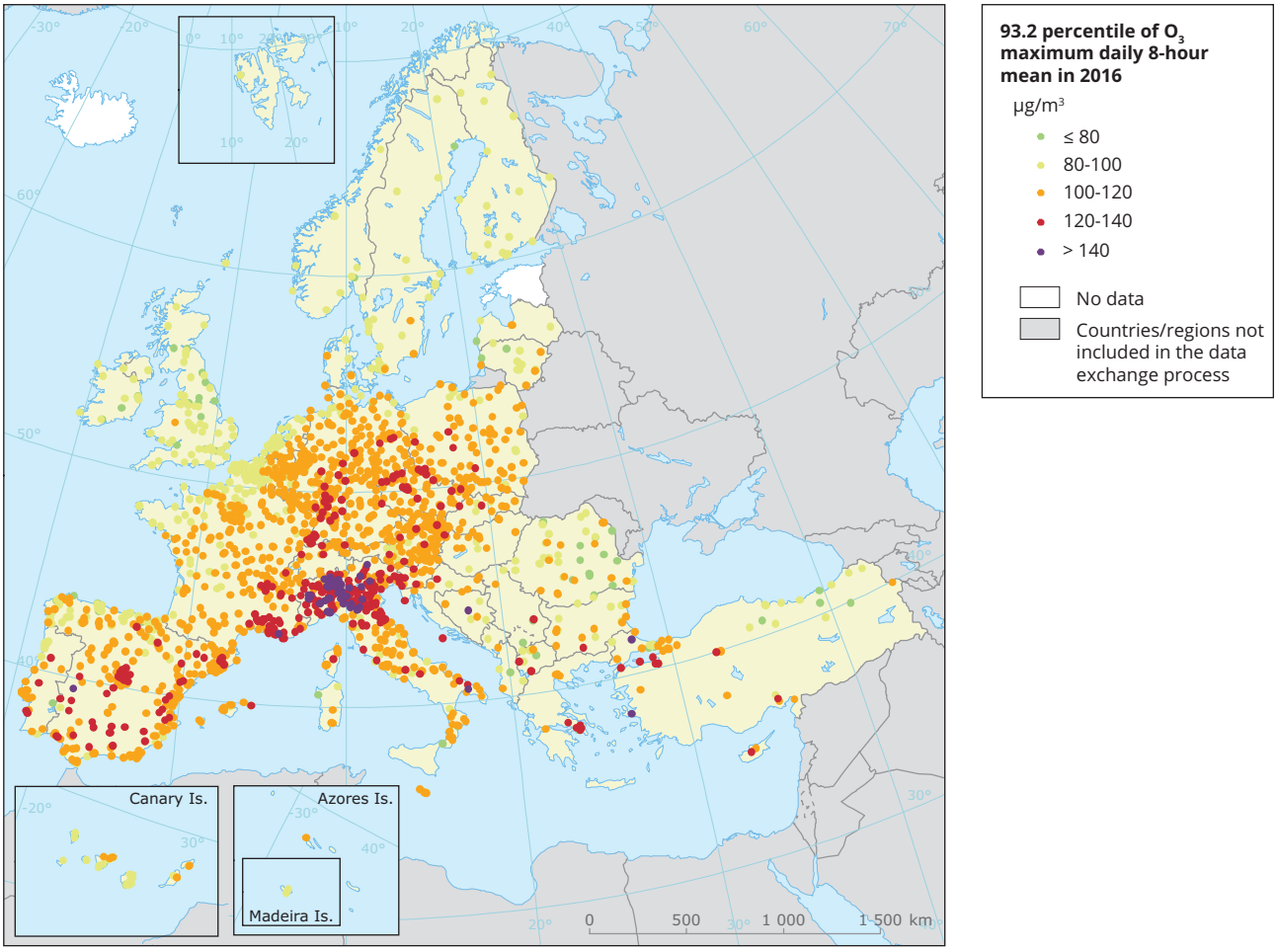
4 Ozone

4.1 European air quality standards and World Health Organization guidelines for ozone

The European air quality standards for the protection of health and the WHO guidelines for O_3 are shown in Tables 1.1 and 1.3, respectively.

The Ambient Air Quality Directive (EU, 2008) also sets targets for the protection of vegetation, shown in Table 1.2. In addition, the CLRTAP (UNECE, 1979) defines a critical level for the protection of forests (see Table 1.2). The vegetation exposure to O_3 levels above these standards and the exposure of forests to O_3 levels above the critical level are assessed in Section 11.1.

Map 4.1 Concentrations of O_3 in 2016



Notes: Observed concentrations of O_3 in 2016. The map shows the 93.2 percentile of the O_3 maximum daily 8-hour mean, representing the 26th highest value in a complete series. It is related to the O_3 target value, allowing 25 exceedances over the 120-µg/m³ threshold. At sites marked with dots in the last two colour categories, the 26th highest daily O_3 concentrations were above the 120-µg/m³ threshold, implying an exceedance of the target value threshold. Only stations with more than 75 % of valid data have been included in the map. The French overseas territories' stations are not shown in the map but can be found at https://www.eea.europa.eu/data-and-maps/dashboards/air-quality-statistics.

Source: EEA, 2018a.

4.2 Status of concentrations

Data for O_3 in 2016 were reported from 2 070 stations in 36 of the EEA-39 countries (all, except Estonia, Iceland and Liechtenstein) and Andorra.

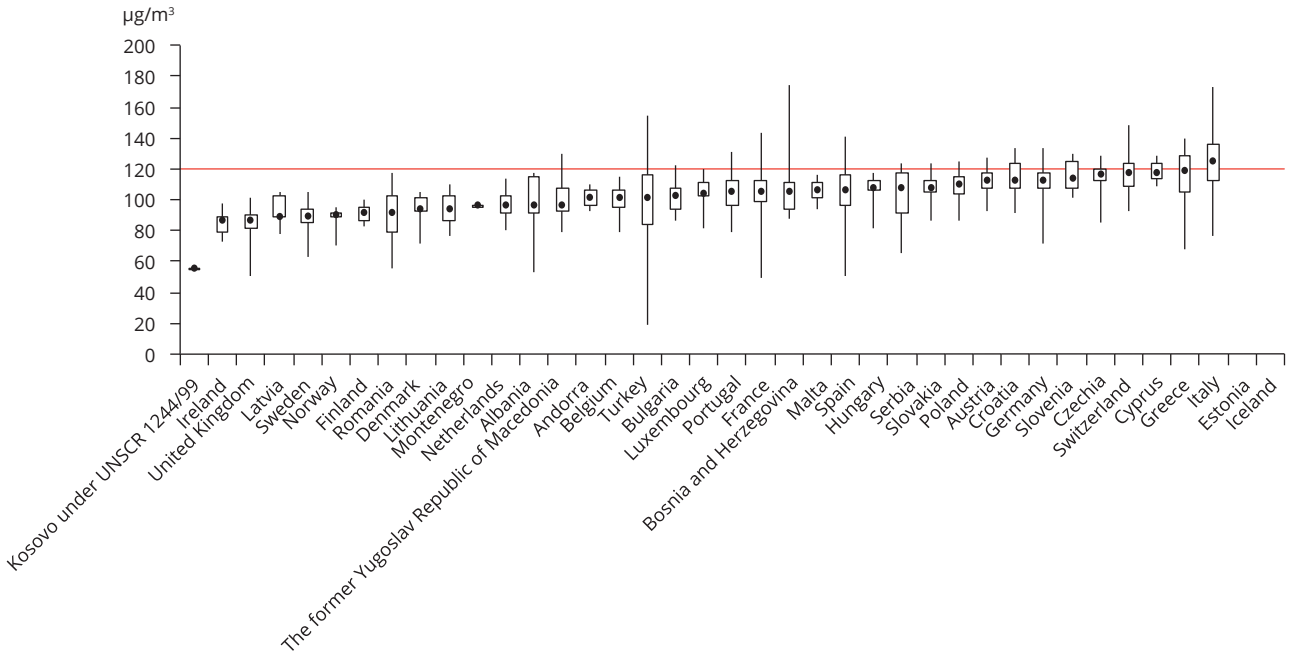
Fourteen Member States and five other reporting countries (see Figure 4.1 and Map 4.1) registered concentrations above the O_3 target value more than 25 times. In total, 17 % of all stations reporting O_3, with the minimum data coverage of 75 %, showed concentrations above the target value for the protection of human health in 2016. This is considerably fewer stations than in 2015 but higher than in 2014. In addition, only 17 % of all stations fulfilled the long-term objective (no exceedance of the threshold level). 87 % of the stations with values above the long-term objective were background stations.

Conformity with the WHO AQG value for O_3 (8-hour mean of 100 µg/m³), set for the protection of human health, was observed in 4 % of all stations and in only two of the 537 rural background stations reported in 2016.

The year 2016 was characterised by the World Meteorological Organization as being the warmest year on record globally (WMO, 2017). On average across Europe, 2016 was the third warmest year to that point (after 2014 and 2015), and the warmest temperature anomaly (+2 to 3 °C) occurred in the Iberian Peninsula during the 2016 summer (CAMS, 2017).

O_3 peak episodes during summer are caused by anthropogenic emissions of precursors (NO_x and VOCs) and, at the same time, are strongly linked to weather conditions and favoured by episodes of

Figure 4.1 O_3 concentrations in relation to the target value in 2016



Notes: The graph is based, for each country, on the 93.2 percentile of the maximum daily 8-hour mean concentration values, corresponding to the 26th highest daily maximum of the running 8-hour mean. For each country, the lowest, highest and median values (in µg/m³) recorded at its stations are given. The rectangles mark the 25th and 75th percentiles. At 25 % of the stations, levels are below the lower percentile; at 25 % of the stations, concentrations are above the upper percentile. The target value threshold set by the EU legislation is marked by the horizontal line. The graph should be read in relation to Map 4.1, as the country situation depends on the number of stations considered.

Source: EEA, 2018a.

Table 4.1 Status of reporting of ozone precursors (VOCs) in 2016

Recommended VOCs	AT	BE	BG	DK	FI	DE	HU	IE	LV	LU	MT	NL	PL	SI	ES	SE	CH	UK
ethane C_2H_6					X	X							X		X	X		X
ethylene $H_2C=CH_2$					X	X							X		X	X		X
acetylene HC=CH					X								X		X	X		X
propane $H_3C-CH_2-CH_3$					X	X							X		X	X		X
propene $CH_2=CH-CH_3$													X		X	X		X
n-butane $H_3C-CH_2-CH_2-CH_3$		X			X	X							X		X	X		X
i-butane $H_3C-CH(CH_3)_2$						X							X		X	X		X
1-butene $H_2C=CH-CH_2-CH_3$													X		X	X		X
trans-2-butene trans-$H_3C-CH=CH-CH_3$		X											X		X	X		X
cis-2-butene cis-$H_3C-CH=CH-CH_3$		X											X		X	X		X
1,3-butadiene $CH_2=CH-CH=CH_2$		X											X		X			X
n-pentane $H_3C-(CH_2)_3-CH_3$	X	X		X		X							X		X			X
i-pentane $H_3C-CH_2-CH(CH_3)_2$	X	X			X	X							X		X	X		X
1-pentene $H_2C=CH-CH_2-CH_2-CH_3$	X	X		X									X		X			X
2-pentene $H_3C-HC=CH-CH_2-CH_3$	X			X											X			
isoprene $CH_2=CH-C(CH_3)=CH_2$		X		X		X							X		X			X
n-hexane C_6H_{14}	X	X		X	X	X							X		X			X
i-hexane $(CH_3)_2-CH-CH_2-CH_2-CH_3$	X	X		X	X								X		X			X
n-heptane C_7H_{16}	X	X		X		X							X		X			X
n-octane C_8H_{18}	X	X		X									X		X	X		X
i-octane $(CH_3)_3-C-CH_2-CH-(CH_3)_2$	X	X		X									X		X			X
toluene $C_6H_5-CH_3$	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
ethyl benzene $C_6H_5-C_2H_5$	X	X		X	X	X	X	X			X		X	X	X	X		X
m+p-xylene m,p-$C_6H_4(CH_3)_2$	X	X	X	X	X	X	X	X			X		X	X	X			X
o-xylene o-$C_6H_4-(CH_3)_2$	X	X		X	X	X	X	X			X		X	X	X	X		X
1,2,4-trimethylebenzene 1,2,4-$C_6H_3(CH_3)_3$	X	X	X	X									X		X			X
1,2,3-trimethylebenzene 1,2,3-$C_6H_3(CH_3)_3$	X		X	X									X		X			X
1,3,5-trimethylebenzene 1,3,5-$C_6H_3(CH_3)_3$	X	X	X	X	X								X		X			X
formaldehyde HCHO													X		X			
total non-methane hydrocarbons THC (NM)						X									X		X	

Notes: Information on benzene is presented in Chapter 8.

AT: Austria, BE: Belgium, BG: Bulgaria, DK: Denmark, FI: Finland, DE: Germany, HU: Hungary, IE: Ireland, LV: Latvia, LU: Luxembourg, MT: Malta, NL: Netherlands, PL: Poland, SI: Slovenia, ES: Spain, SE: Sweden, CH: Switzerland, UK: United Kingdom.

An 'X' indicates that the pollutant was reported by the corresponding country.

warm, stagnant high pressure. CAMS (2017) estimated that the worst O_3 episode in 2016 occurred between 25 and 28 August, leading to concentrations above the information threshold (Table 1.1) in a large number of stations across western and central Europe and even in northern Germany. Traffic and industrial emissions were considered the main contributors to this O_3 episode event.

For more information on the causes and trends of O_3 pollution in Europe and throughout the Mediterranean area, as well as O_3 abatement strategies, see Chapter 5.

4.3 Ozone precursors

With the objective of analysing any trend in O_3 precursors, checking the efficiency of emission reduction strategies, checking the consistency of emission inventories and helping attribute emission sources to observed pollution concentrations, the Ambient Air Quality Directive (EU, 2008) establishes the obligation of installing at least one sampling point per Member State, to supply data on concentrations of some VOCs, as they are O_3 precursors.

The recommended VOCs for measurement are presented in Table 4.1. C_6H_6 is also recommended but, as a regulated pollutant, is analysed in Chapter 8. For the rest of the recommended VOCs, measurements have been reported for at least two countries in 2016. The most commonly reported compounds are toluene (reported by 18 countries), ethyl benzene, m+p-xylene and o-xylene (13 countries each). Spain is the only country that reported all the recommended VOCs in 2016. Poland reported all except 2-pentene and THC (NM); and the United Kingdom all except 2-pentene, formaldehyde and THC (NM).

The situation for the 30 recommended VOCs, excluding benzene, and the 18 reporting countries is summarized in Table 4.1. The reported concentrations can be found at https://www.eea.europa.eu/data-and-maps/dashboards/air.

Photo: © Daniela di Sarra, NATURE@work /EEA

5. Ozone pollution in Europe: special focus on the Mediterranean

As shown in the previous chapter, one of the regions where highest O_3 concentrations are normally measured is the Mediterranean area during spring and summer. This is the result of different atmospheric processes, which are further explained below.

However, some years have witnessed high concentrations in most parts of central Europe (see for instance the situation in 2015; EEA, 2017a) because of interannual meteorological variability. This is why a thorough analysis of trends and changes in O_3 concentration has to consider all European regions. Otero et al. (2016) reported the maximum temperature as being the parameter most directly related to high O_3 concentrations in central Europe, whereas in the western Mediterranean region, O_3 concentrations were more related to the concentrations recorded the day before (this denotes the vertical recirculation of air masses as a major cause; Millán et al., 2000; Querol et al., 2018, among others).

Finally, despite the significant O_3 policy and the scientific attention O_3 has received at European and international levels, not many measures have been implemented to reduce O_3 concentrations and priority has been given to other pollutants, such as PM or NO_2. This could be for several reasons. First of all, fewer premature deaths are attributed each year to exposure to O_3 than to exposure to $PM_{2.5}$ or NO_2 (see Chapter 10 for 2015); and the impact on the GDP of the costs associated with PM-attributable health effects is estimated to be 5 %, while it is 0.2 % for O_3 (World Bank, 2016). Secondly, O_3 episodes have stronger impacts on rural areas (where fewer people are exposed) than on urban areas. However, the impact of this pollutant on crops and vegetation, especially in rural areas, can be significant. Lastly, and maybe most importantly, because of the nature of O_3, local measures alone are not enough to tackle the problem and actions at different levels of governance (i.e. regionally and internationally) are needed. This makes the definition and implementation of abatement measures more difficult.

5.1 Tropospheric ozone pollution

Tropospheric (ground-level) O_3 is a secondary pollutant, which is not directly emitted into the atmosphere, but is formed from chemical reactions in the presence of sunlight, and natural and anthropogenic precursor gases (mainly NOx and VOCs). Tropospheric O_3 is characterised by complex formation mechanisms based on the photo-oxidation of VOCs in the presence of NO_x, following non-linear formation pathways: NO_x are involved in O_3 formation but also removal through titration (the reaction of O_3 with NO to form NO_2 and O_2) (Monks et al., 2015). At the continental scale, CH_4 and CO also play a role in O_3 formation, which is intensified in summer resulting in characteristic O_3 episodes (ETC/ACM, 2018d).

As a result of its chemical properties, O_3 is a pollutant that causes harm to human health (WHO, 2008) and ecosystems (e.g. Nali et al., 2002; Scebba et al., 2006) (see Sections 10.2 and 11.1). Consequently, the WHO and the EU have set standards for O_3 (Tables 1.1, 1.2 and 1.3). The number and variety of standards and guidelines in Tables 1.1, 1.2 and 1.3 reflect the complexity linked to the quantification and regulation of this atmospheric pollutant.

The status of O_3 concentrations in Europe in 2016 was presented in Chapter 4.

O_3 pollution has an important spatial dimension, as O_3 formation requires time for interaction between sunlight and precursor gases, which generally occurs during air mass transport and ageing. This process involves not only local and regional air masses, but also long-range and even hemispheric air mass transport (Figure 5.1).

Large urban and industrial agglomerations are major emitters of precursor gases through traffic, industry, airports or shipping activities, and biomass combustion plants, among other things. Precursors are then transported by local/regional air mass flows away from the urban agglomerations and towards

suburban and rural areas, which are impacted by O_3 pollution episodes (although in large cities O_3 thresholds may also be exceeded). As a result, establishing a link between the emitters of precursor gases (generally, urban areas) and the populations exposed to high O_3 concentrations (generally, rural areas), is not always straightforward. Examples of this may also be found on different spatial scales: Asian emissions impacting O_3 concentrations in North America (Lin et al., 2017); precursor emissions from Italy and France impacting O_3 concentrations in Spain (Millán et al., 1997); long-range transport of O_3 and its precursors influencing the background O_3 concentrations in Europe (UNECE, 2010); or urban emissions resulting in O_3 episodes in surrounding rural areas (Querol et al., 2016). The main complexity of this system arises from the fact that all these contributions are mixed and they all contribute to surface O_3 concentrations with different proportions that may vary significantly over time and space across the study area. However, it seems that for the very acute O_3 episodes in specific areas of the Mediterranean the local-regional emissions have a key role in exceeding target values (Querol et al., 2016, 2018).

5.2 Ozone pollution in the Mediterranean region

The Mediterranean is among the most climatically sensitive regions of Europe, often exposed to multiple stresses, such as simultaneous water shortage and air pollution exposure (IPCC, 2013). It is characterised by a large variety of VOC and NOx emissions influencing O_3 formation and destruction (Sahu and Saxena, 2015; Sahu et al., 2016), as well as by many hours of sunshine and specific atmospheric recirculation patterns (Millán et al., 2000; Gangoiti et al., 2001; Querol et al., 2018). These factors result in higher O_3 concentrations (see Section 4.2) and more frequent tropospheric O_3 episodes compared with elsewhere in Europe, with different patterns in the west and east of the Mediterranean basin.

The western Mediterranean basin is characterised by frequent sea-land breezes that transport air masses, including O_3 precursor gases, from coastal urban agglomerations towards inland suburban and rural areas. In addition to this, the vertical recirculation of pollutants impacts surface O_3 concentrations (Millán et al., 1996, 2000). High O_3 episodes in this region are linked to the combination of one or more of these mechanisms (ETC/ACM, 2018d; Querol et al., 2018):

1. local/regional photochemical production and transport at surface level from coastal agglomerations towards inland regions;

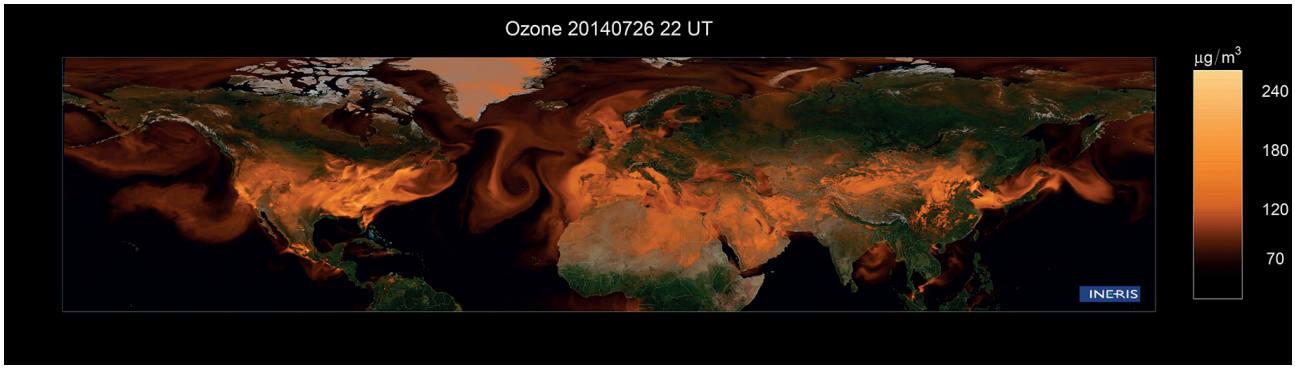
2. transport of O_3 from higher-altitude atmospheric layers (1 500-3 000 m above ground level), originating from air mass re-circulation in the previous day(s);

3. long-range transport of O_3 and its precursor gases.

In the eastern Mediterranean area, the nature of O_3 episodes during summer depends on the relative strength of the high-pressure system covering the eastern Mediterranean and Balkan area:

4. strong pressure gradient — northerly winds dominate, creating good ventilation in the Athens basin (Kallos et al., 2014). These circulations give rise to episodes of O_3 transport from other regions, as described in point 3 above for the western Mediterranean basin.

Figure 5.1 Ozone modelled over the Northern Hemisphere with the Chimère air quality model at a spatial resolution of 10 km, July 2014



Source: INERIS (https://www.ineris.fr/fr/lineris/actualites/la-qualite-de-lair-racontee-par-la-modelisation).

5. weak pressure gradient — local-regional O_3 events prevail (similar to mechanism 1, described for the western Mediterranean basin).

6. stratospheric O_3 contributions have been reported to increase surface O_3 concentrations during specific meteorological scenarios (Kalabokas et al., 2013, 2015; Zanis et al., 2014). This transport has been associated with large-scale subsidence within strong northerly winds (see point 4). The affected layers are drier than average and show negative temperature anomalies.

As a result, the existing literature concludes that both local/regional and long-range transport episodes are recorded across the Mediterranean basin, with different frequencies in the east and west ([18]).

A recent study (ETC/ACM, 2018d) analysed six coastal areas under the influence of major cities (Valencia, Barcelona, Marseille, Rome, Brindisi/Taranto and Athens) across the Mediterranean basin. The aim was to understand the abovementioned mechanisms, the different patterns observed in episode formation in the western and eastern Mediterranean regions and their potential impact in the design of mitigation strategies and measures. Urban stations were selected in each city to represent the source of urban pollutants, as well as suburban and rural stations to represent areas where O_3 pollution was influenced from the main urban area.

During O_3 episodes, an increasing gradient in O_3 concentrations was frequently observed from urban to rural stations. This gradient demonstrates the mechanism whereby O_3 precursors are emitted in urban areas, O_3 concentrations consequently increase, on account of solar radiation and transport from urban to rural areas by means of sea breeze circulations. This is prevalent in the western Mediterranean regions. Meso-scale or long-range transport of O_3 concentrations under anticyclonic conditions, with less influence of sea breeze circulations and without vertical transport, was also observed, with a relatively higher frequency in the eastern region.

These results have implications from the point of view of mitigation strategies to reduce O_3 impacts. In the case of episodes dominated by local/regional transport between urban and rural areas, mitigation strategies should be directed at reductions in precursor gas emissions in urban and industrial areas. In the case of episodes dominated by regional and long-range transport, O_3 concentration forecasts and behavioural measures (e.g. advising people avoid physical activity), together with regional-scale measures targeted at reducing background concentrations, may be considered more effective strategies. However, given that both types (local formation and regional transport) of episodes can occur, a combination of measures (emission reductions, coupled with forecasts and behavioural changes) would constitute the optimal approach, as further explained below. In either case, structural measures (permanent reductions in VOCs and NO_x) are considered the most effective ways to tackle this issue in an effective, long-term, sustainable manner.

5.3 Abatement strategies

The complexity of the processes described above, and the fact that meteorology in a given year might drastically enhance or reduce the number and intensity of O_3 episodes and affect O_3 concentrations, may counteract or hide the possible effect of the abatement of anthropogenic precursors on reducing O_3 concentrations. If emission abatement measures are not implemented, the intensity (and possibly the frequency) of O_3 episodes during heatwaves may increase considerably.

5.3.1 Long -term measures

To reduce air pollution, including O_3, the EU legislation sets long-term measures based on, for example, new technologies or reducing energy consumption (for more information, see Section 1.5). These measures are also addressed by international agreements, such as the CLRTAP, which target reducing emissions of O_3 precursors (NO_x and VOCs). The EU NEC Directive (EU, 2016) set reduction commitments for 2020 agreed under the CLRTAP's Gothenburg Protocol for EU Member States, and more ambitious reduction commitments for 2030. In addition, structural measures to tackle O_3 pollution in an effective and long-term, sustainable manner are available and, to some extent, have been implemented. Examples of such measures are de-NO_x technologies for industry and power generation, or reducing NO_x emissions with better on-road engine technologies, congestion charges (such as those in Stockholm or Milan, for example), or improving urban freight distribution.

([18]) Additional research applying a consistent methodology in the two Mediterranean regions is necessary to provide statistically robust conclusions on the frequency of both episodes in the two different regions.

The long-term objectives for O_3 cannot be met without additional action worldwide and an integrated approach. The last CLRTAP Scientific Assessment Report (Maas and Grennfelt (eds), 2016) emphasizes the need for an integrated approach on air quality and climate mitigation measures that goes beyond the current domain of the CLRTAP and includes other major emitters globally, for example, measures targeting CH_4 would be beneficial for both climate change mitigation and O_3 reduction ([19]).

5.3.2 Short-term measures

On a local scale, short-term action plans and measures can be implemented before and during an episode to rapidly respond to pollution episodes (such as those described under Section 5.2), provided the episodes can be forecast in advance. However, evaluating the efficiency of mitigation measures for O_3 is not straightforward because of the complexity and non-linearity of O_3 production and destruction processes. It requires a good understanding of the atmospheric dynamics, including meteorological conditions, and of the regional and local O_3 production systems governing the episodes (see Box 5.1).

Local short-term measures target O_3 episodes through reducing precursor emissions (ASPA, 2006; Lasry et al., 2007), as well as reducing NO_x and particle concentrations, which may have an indirect impact on O_3 concentrations. Reductions in O_3 precursor emissions can be obtained from targeting road traffic, e.g. through vehicle access restrictions and imposing speed limits. However, the effectiveness of these measures is generally presented in terms of NO_x or VOC emission reductions and not in terms of O_3 mitigation. Measures for the industrial processes sector and for the residential combustion sector can also significantly reduce VOC emissions.

The timing of the measures is also relevant in the case of southern European regions: Lasry et al. (2007) showed that measures implemented after 14:00 (local time) are inefficient in reducing O_3 on the same day because pollutants that participate in the formation of the O_3 plume are those released before 14:00. This aspect is important when designing and implementing regional air quality plans: an example may be found in the O_3 action plans proposed by the French Bouches du Rhône district, where air quality forecasts produced at 11:00 are decisive for the deployment of short-term measures in the region (EEA, 2018b). According to their air quality plan, the use of forecasting tools allows this region to trigger emission reduction strategies before O_3 thresholds are exceeded.

Finally, the literature shows varying efficiency of individual measures, such as restrictions on large industrial installation emissions, alternate licence plate vehicle access restrictions and restrictions on heavy-duty traffic transit, to achieve reductions in emissions of O_3 precursor gases. The specific short-term measures to reach these reduction levels should be analysed on a case-by-case basis; however, especially in NO_x-driven areas, similar measures to those used to abate NO_x in winter might be effective.

5.4 Ozone trends across Europe

The evolution of O_3 concentrations across Europe over the past couple of decades raises a number of concerns. Despite the fact that O_3 precursor emissions (NO_x and VOCs) declined in the EU-28 by about 40 % between 2000 and 2016 (Section 2.1), a similar trend cannot be found for most of the O_3 metrics. Furthermore, the fraction of the urban population in Europe exposed to levels exceeding the WHO air quality guideline (8-hour daily maximum above 100 µg/m^3) remained consistently over 95 % during that period (EEA, 2018f; see also Section 9.1).

However, different studies (Sicard et al., 2013; Paoletti et al., 2014; EMEP, 2016) found that there is evidence, based on measurements from rural background stations, that O_3 peaks did decline across Europe, especially in rural areas (where most O_3 peaks are recorded). This is shown in Figure 5.2, which presents the evolution of the fourth highest daily maximum of the 8-hour running mean (fourth highest MDA8) as an indicator of O_3 peaks. The decline in the magnitude of high O_3 episodes was found to be of the order of 10 % at European Monitoring and Evaluation Programme (EMEP) stations for both the periods 1990-2001 and 2002-2012. The annual mean in the period 1990-2012 remained quite flat (EMEP, 2016).

([19]) In that sense, and to comply with the 2020 and 2030 objectives for reductions in emissions of greenhouse gases, the EU has put in place the following mechanisms: the Emissions Trading System (ETS) (EU, 2003), the Effort Sharing Decision (ESD) (EU, 2009) and the Effort Sharing Regulation (ESR) (EU, 2018). The ETS is a central instrument of the EU's policy to fight climate change and achieve cost-efficient reductions in greenhouse gas emissions. It is the world's biggest carbon market and it limits emissions from more than 11 000 heavy energy-using installations (power stations and industrial plants) in the EU-28 plus Iceland, Liechtenstein and Norway, and airlines in these countries. Furthermore, the ESD establishes annual greenhouse gas emission targets for Member States for the period 2013-2020, and the ESR for the period 2021-2030. These targets concern emissions from most sectors not included in the EU ETS, such as transport, buildings, agriculture and waste (thus addressing CH_4).

Box 5.1 Scale for action: a case study for the Barcelona region

Short-term actions are generally applied on a local scale for practical reasons regarding the ease of implementation of restrictive measures. However, given the regional nature of O_3 pollution, the efficiency of reductions in emissions strictly applied in urban areas is limited, as shown in a case study for the Barcelona area (Spain) (ETC/ACM, 2018d). This area was the focus of a field campaign in 2015 to describe O_3 formation and transport patterns. Two episodes were studied: one with predominant local influence (mechanism 1 in 5.2); and another with more external influence (mechanism 3).

The chemistry transport model Chimère was used to explore the efficiency of potential mitigation measures (reduction of 30 % in anthropogenic emissions of NO_x and VOCs) for both O_3 episodes and applied (1) to the Barcelona urban area, (2) to the greater Barcelona region (including the city itself), (3) to non-Spanish terrestrial emissions, or (4) to maritime emissions. Various time lags were tested for these emission reductions, reaching up to 3 days ahead of the O_3 peak.

For the two O_3 episodes investigated, the largest potential for mitigation was at the scale of the greater Barcelona region. Reducing the emissions from outside the region was also found to be significant in the case of episodes with external influence. Reductions limited to the Barcelona urban area were less efficient than those applied to the greater region and even led to an increase in O_3 levels inside the city. This is because a reduction in NO_x emissions implies a reduction in both NO_2 and NO emissions. This means that there will be less NO available to react with O_3 (to form NO_2 and O_2) and therefore less O_3 is removed close to the traffic NO_x emissions.

For the episode dominated by local emissions, the model indicated benefits from reducing O_3 when initiating emission reductions 1 day before the expected O_3 peak (with no additional benefit if the reductions were started 2 or 3 days before).

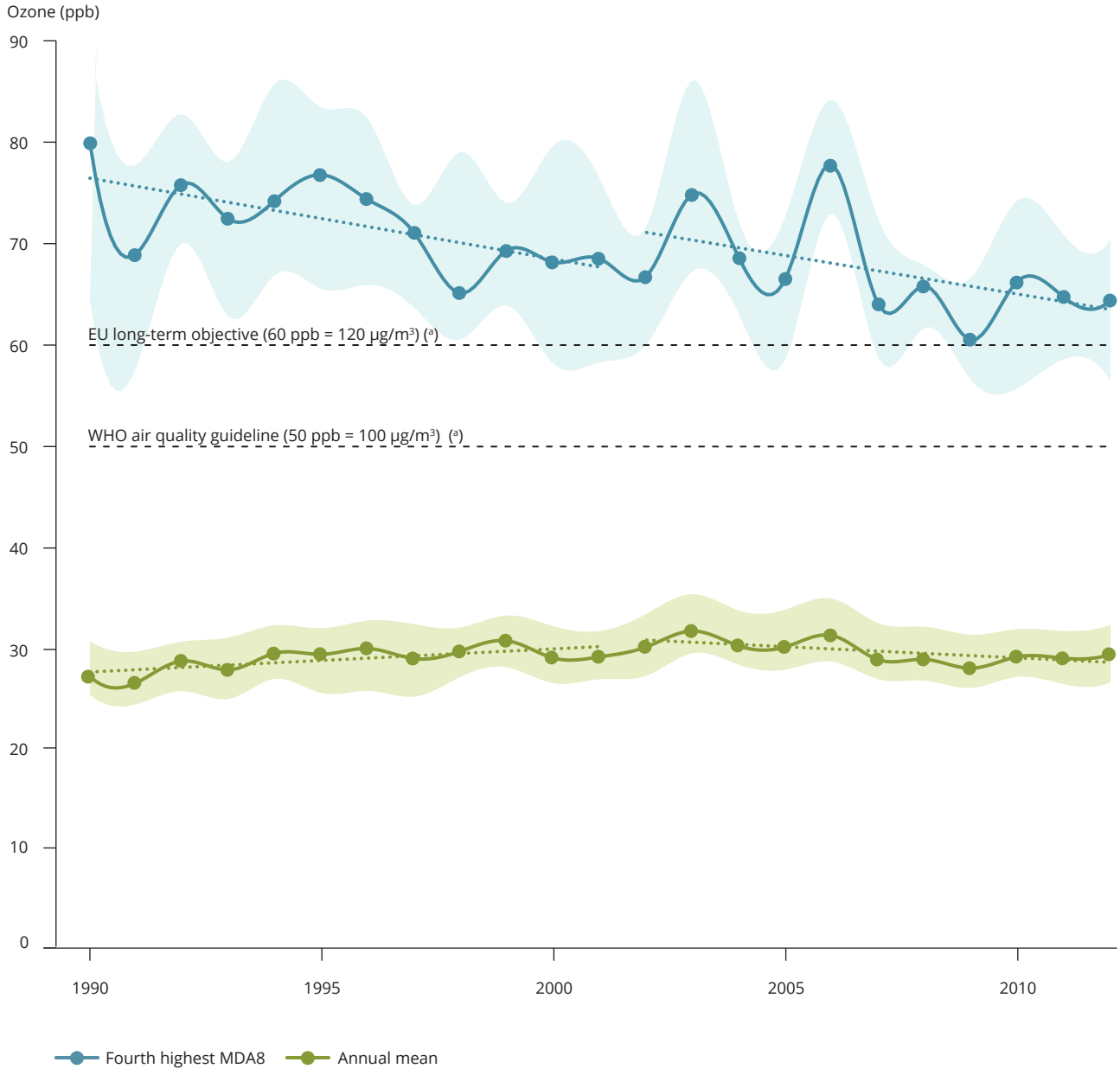
This is an example of how modelling can be used to help implement abatement measures. Nevertheless, modelling needs continuous improvement so it can properly reproduce, at the required scale, the complex atmospheric processes involved in O_3 formation and transport.

When considering all types of station, and not only EMEP rural background stations (ETC/ACM, 2015a), increases in the annual mean concentrations were widespread in the 1990s and constant levels were observed in the 2000s. The increase in the 1990s is especially pronounced at urban background stations and traffic sites during winter, pointing towards the role of reduced titration (lower O_3 destruction at night as a result of NO_x emission reductions) because of changes in the ratio NO/NO_2 in the emissions of the vehicle fleets. On average, daily O_3 maxima were already declining in the 1990s, but the relative trend intensified over the period 2002-2012. The trends and responses are, however, diverse depending on the O_3 indicators evaluated (Lefohn et al., 2017) — the trends for SOMO35 (for health) and AOT40 (for ecosystems) being somewhat between those of the O_3 annual mean and peaks.

It should be noted that the statistical significance of the trend was limited at a large proportion of sites, because of the strong interannual variability in O_3 levels. The decrease in the O_3 peak, apparent in Figure 5.2, was only significant at 20 % of monitoring sites over the periods 1990-2001 and 2002-2012 (EMEP, 2016). These conclusions will therefore need to be supported further in the future using longer time series. In addition, most of the cited assessments focused on the period 1990-2012, when the monitoring network had substantial geographical inhomogeneities (notably a lack of dense observations across southern Europe).

Air quality models can provide valuable information to further our understanding of O_3 trends. Using the Eurodelta multi-model ensemble (ETC/ACM, 2017c) coordinated under EMEP, it was possible to quantify, for different European regions, the relative importance of (1) European emission changes, (2) meteorological conditions and (3) intercontinental influx (represented by the boundary conditions) (Figure 5.3). For both O_3 annual mean and peaks, European emission changes were found to have contributed to the decreasing trends. Only one exception was found, over southern United Kingdom, which is particularly exposed to the titration effect because of the strongly NO_x- saturated regime. O_3 peaks were found to be weakly influenced by the intercontinental influx. Meteorological conditions did play a role but only to contribute to the decreasing trend. The robustness of this conclusion was further confirmed with two independent methods relying on either alternative chemistry-transport simulations, with the EMEP model to compute the trends in the year-to-year deviation from climatology, or on a statistical decomposition using exclusively O_3 observations (ETC/ACM, 2018a).

Figure 5.2 Ozone annual mean (green) and peaks (blue) recorded at 55 EMEP rural sites in 1990-2012



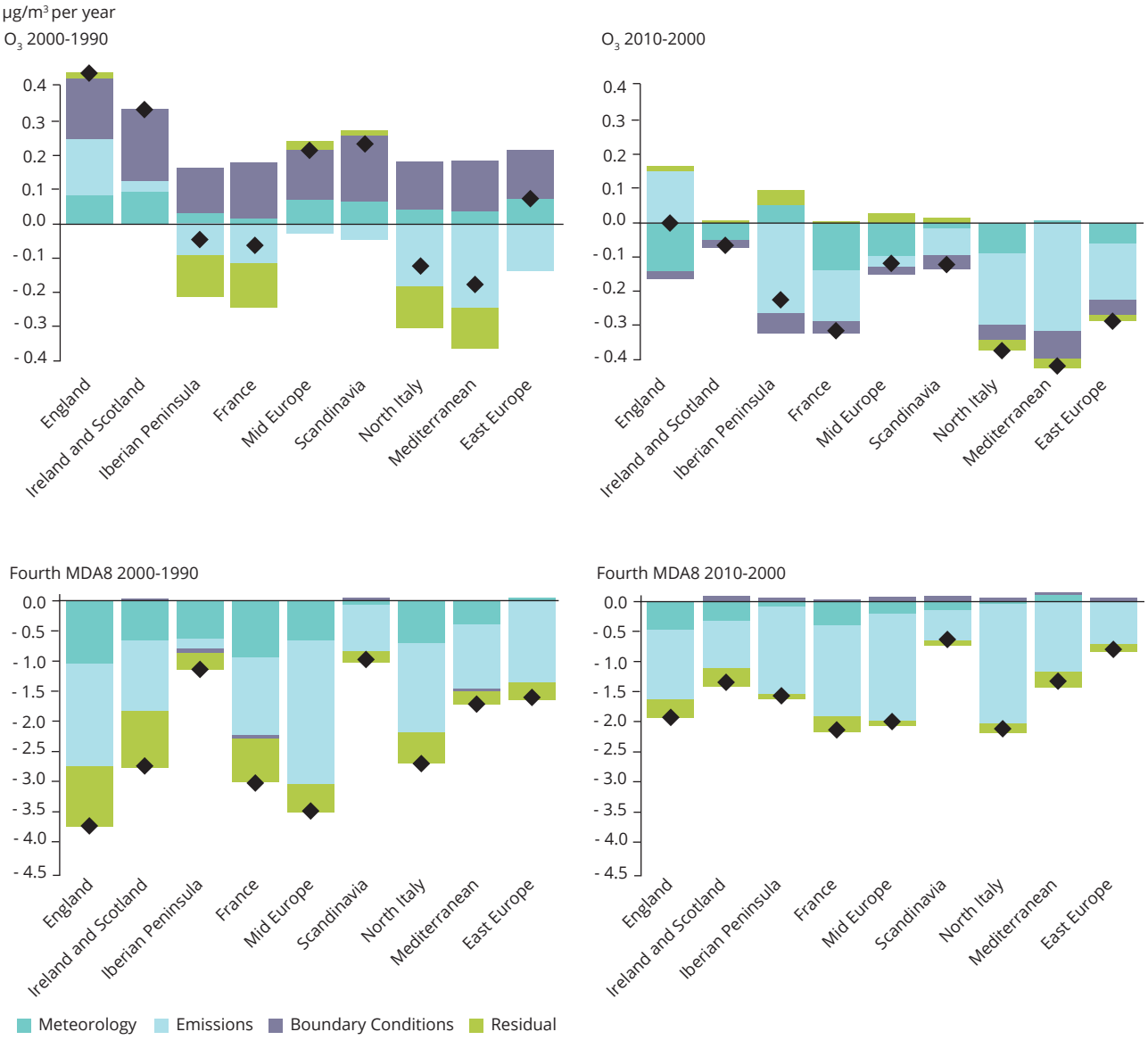
Source: EMEP, 2016.

Notes: Fourth highest MDA8 represents the fourth highest daily maximum of the 8-hour running mean and is used as an indicator of ozone peaks.

(a) For more information, see Tables 1.1 and 1.3.

In conclusion, for the annual mean concentrations, increases were widespread in the 1990s and constant levels were observed in the 2000s; however, an encouraging trend in the reduction in the O_3 peak was observed in Europe during the period 1990-2012 . The levels remain, however, above the WHO air quality guideline (50 ppb = 100 µg/m³) and the EU long-term objective (60 ppb = 120 µg/m³), indicating that further efforts are needed. There is also a discrepancy between observed O_3 trends (10 % reduction between 2001 and 2012) and emission changes (30% reduction over the same period 2001-2012). Even so, it can be stated with confidence that the decreasing trend in O_3 was mainly caused by the reduction in the European emissions of O_3 precursors.

Figure 5.3 Attribution of ozone trend to key driving factors



Notes: The graphs on the top represent the modelled trend of ozone annual mean; the graphs on the bottom represent the modelled trend of O_3 peaks during summertime (April-September mean of the fourth highest daily maximum of the 8-hour running mean (Fourth MDA8)). In the 1990s (left) and in the 2000s (right).

The black diamond indicates the net trend (µg/m³ per year), all factors considered.

6 Nitrogen dioxide

6.1 European air quality standards and World Health Organization guidelines for nitrogen dioxide

The European air quality standards, set by the Ambient Air Quality Directive (EU, 2008) for the protection of human health, and the WHO guidelines for NO_2 are shown in Tables 1.1 and 1.3, respectively.

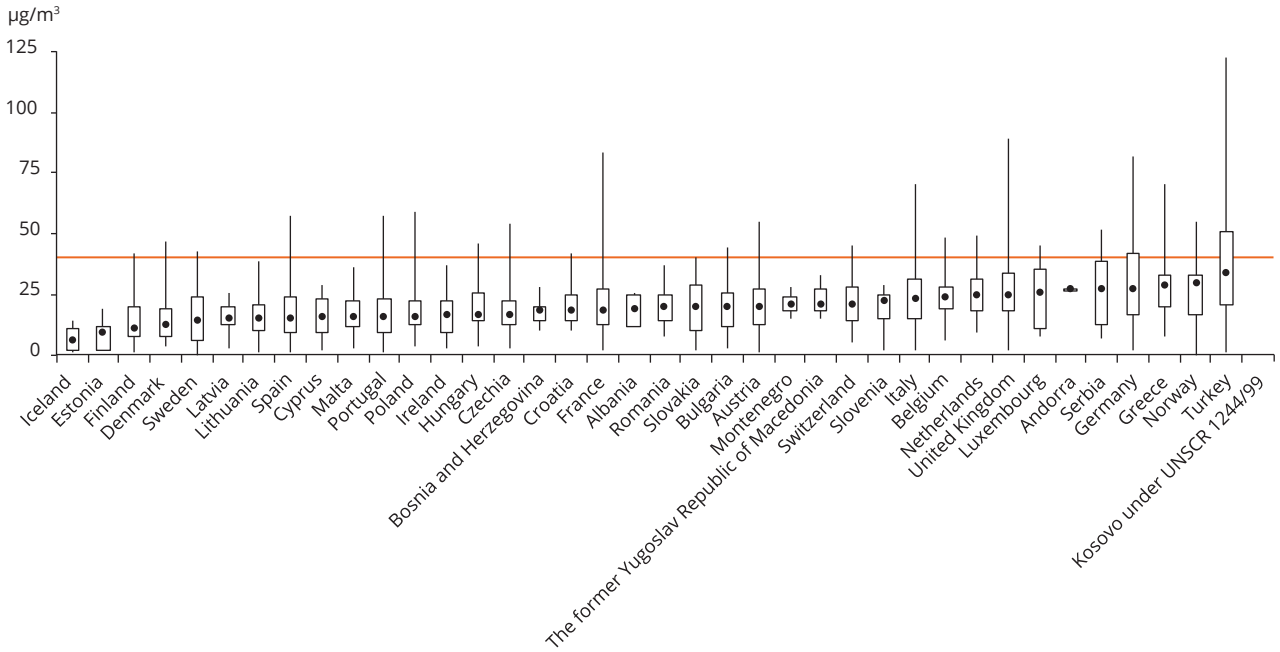
The Ambient Air Quality Directive (EU, 2008) also sets a critical level for NO_x for the protection of vegetation, shown in Table 1.2. The vegetation exposure to NO_x concentrations above this standard is assessed in Section 11.4.

6.2 Status of concentrations

All the EEA-39 countries (except Liechtenstein and Kosovo) and Andorra submitted NO_2 data in 2016 with a minimum coverage of 75 % of valid data (a total of 3 083 stations). Nineteen of the EU Member States and four other reporting countries (see Figure 6.1) recorded concentrations above the annual limit value. This happened in 11.5 % of all the stations measuring NO_2. Map 6.1 shows that the stations with concentrations above the annual limit value continue to be widely distributed across Europe in 2016, as in previous years.

None of the stations with concentrations above the annual limit value were rural background stations. Several urban background stations in Turkey measured some of the highest annual mean concentrations in 2016. Except for those cases, the highest concentrations, as well as 88 % of all values above the annual limit value, were observed at traffic stations. Traffic is a major source of NO_2 and NO (which reacts with O_3 to form NO_2). Furthermore, 98 % of the stations with values above the annual limit value were located in urban or suburban areas. Therefore, reductions in NO_2 concentrations and

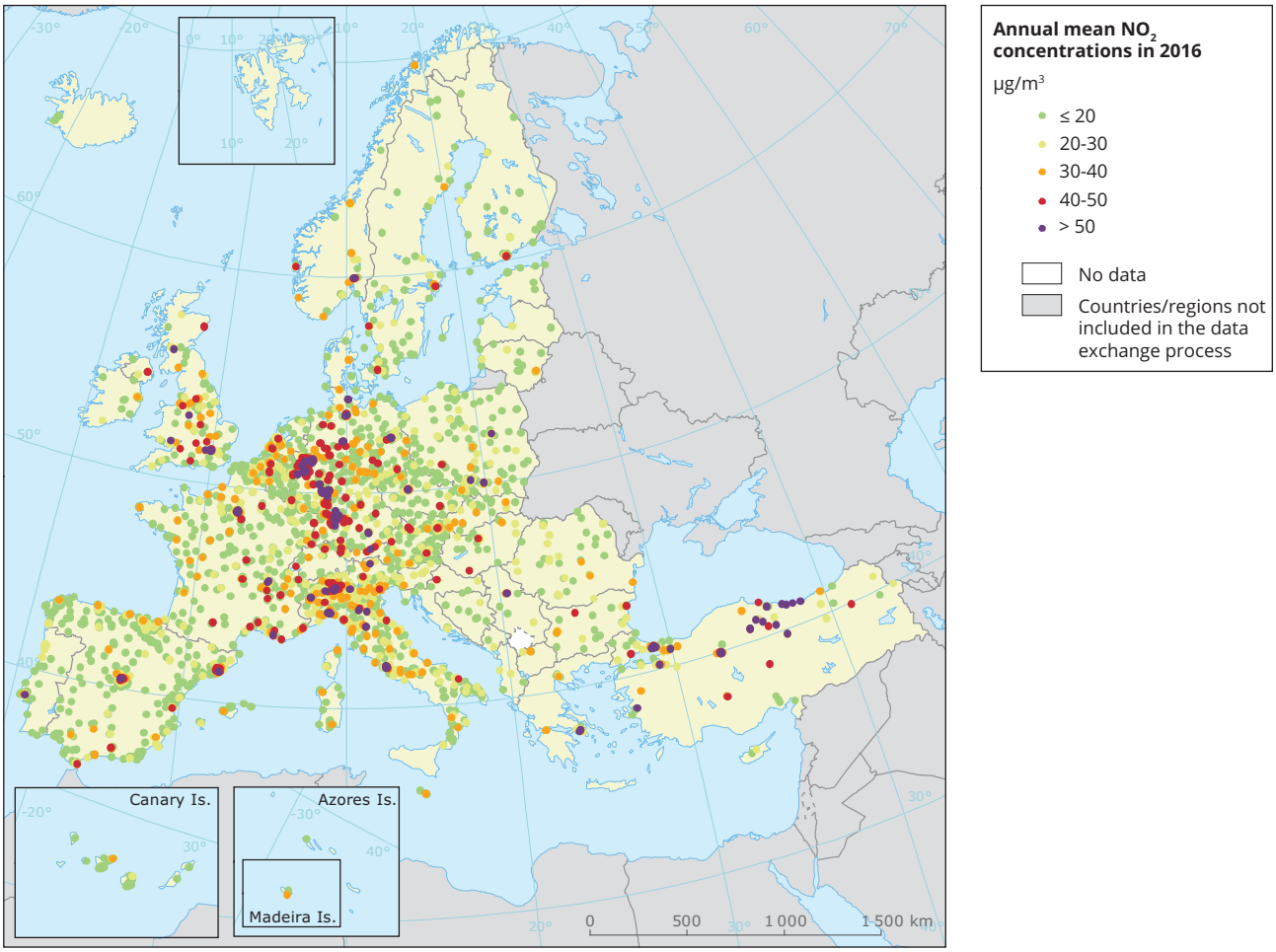
Figure 6.1 NO_2 concentrations in relation to the annual limit value in 2016



Notes: The graph is based on the annual mean concentration values. For each country, the lowest, highest and median values (in µg/m³) recorded at its stations are given. The rectangles mark the 25th and 75th percentiles. At 25 % of the stations, levels are below the lower percentile; at 25 % of the stations, concentrations are above the upper percentile. The limit value set by EU legislation (equal to the WHO AQ guideline) is marked by the horizontal line. The graph should be read in relation to Map 6.1, as the country situation depends on the number of stations considered.

Source: EEA, 2018a.

Map 6.1 Concentrations of NO_2, 2016



Notes: Observed concentrations of NO_2 in 2016. Dots in the last two colour categories correspond to values above the EU annual limit value and the WHO AQG (40 µg/m³). Only stations with more than 75 % of valid data have been included in the map. The French overseas territories' stations are not shown in the map but can be found at https://www.eea.europa.eu/data-and-maps/dashboards/air-quality-statistics

Source: EEA, 2018a.

exceedances are often focused on traffic and urban locations, as mentioned in Section 1.6.

Concentrations above the hourly limit value were observed in 2016 in 1.3 % of all (2 911) reporting stations, mostly at urban traffic stations, except for 16 urban background stations in Turkey and one in Serbia. They were observed in eight countries ([20]).

6.3 Contribution of nitrogen oxides emissions to ambient nitrogen dioxide concentrations

As is true for PM, the contributions from the different emission sources and sectors to ambient air concentrations depend, not only on the amount of pollutant emitted, but also on the emission conditions (e.g. height of emission points), meteorological conditions and the distance to the receptor site. The road transport sector continued to contribute the highest proportion of NO_x emissions (39 % in the EU-28; see Figure 2.4) in 2016, followed by the energy production and distribution sector, and the commercial, institutional and households sector (see Section 2.2). However, the contribution of the road transport sector to population exposure to ambient NO_2 concentrations, especially in urban areas, is considerably higher, because its emissions are close to the ground and are distributed across densely populated areas.

([20]) These were observed in Turkey (23 stations), Spain (four), France (three), the United Kingdom (three), Germany (two), Norway (two), Italy (one), and Serbia (one).

7 Benzo[*a*]pyrene

7.1 European air quality standard and reference level for benzo[*a*]pyrene

The target value for BaP for the protection of human health and the estimated reference level ([21]) are presented in Tables 1.1 and 1.3.

7.2 Status of concentrations

Twenty-five Member States (all except Greece, Romania and Malta ([22])) and two other reporting countries (Norway and Switzerland) reported BaP data ([23]) with sufficient data coverage ([24]) for 2016, from a total of 698 stations ([25]).

A total of 13 Member States measured concentrations above 1.0 ng/m^3 in 2016 (see Figure 7.1). As in previous years, values above 1.0 ng/m^3 are most predominant in central and eastern Europe. The concentrations measured at many Polish stations persist at very high levels, well above the target value.

Similarly to 2015, concentrations above 1.0 ng/m^3 were measured at 31 % of the reported BaP measurement stations in 2016 (see Map 7.1), mainly at urban and suburban stations (94 % of all stations with values above 1.0 ng/m^3 were in urban and suburban locations).

Regarding the reference level, all reporting countries, except for the Netherlands and Sweden, have at least one station with concentrations above 0.12 ng/m^3. Only 14 % of the reported stations in 2016 had annual concentrations below the reference level.

Ambient air concentrations of BaP are high mostly because of emissions from the domestic combustion of coal and wood (EEA, 2016), although for some specific countries (mostly in southern Europe) the contribution of agricultural waste burning is also relevant (EEA, 2017a).

7.3 Reporting of other polycyclic aromatic hydrocarbons

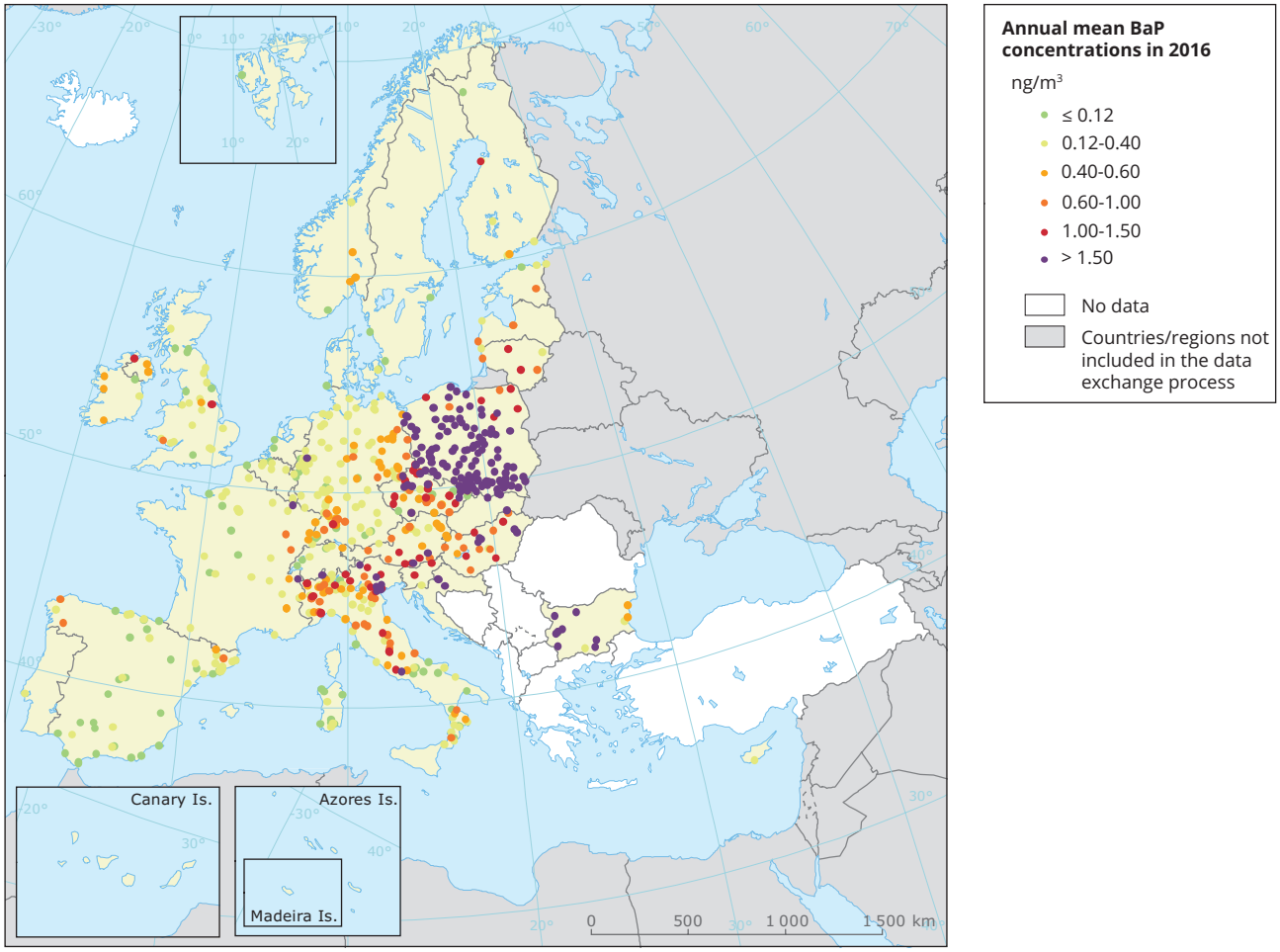
To assess the contribution of Bap in ambient air, the Ambient Air Quality Directive (EU, 2004) outlines an obligation for Member States to monitor other relevant PAHs at a limited number of measurement sites. The compounds to be measured shall include at least: benzo(a)anthracene, benzo(b)fluoranthene, benzo(j)fluoranthene, benzo(k)fluoranthene, indeno(1,2,3-cd)pyrene, and dibenz(a,h)anthracene.

In 2016, at least 16 countries reported measurements of one of the PAHs indicated in the Ambient Air Quality Directive (EU, 2004) (measured as PM_{10} (aerosol)) ([26]). Germany, Poland, Spain and the United Kingdom reported the six compounds. Austria reported all, except benzo(k)fluoranthene; Croatia, Cyprus ([27]), Finland, Latvia, Lithuania and Portugal reported all except benzo(j)fluoranthene. The remaining reporting countries were Denmark, Hungary, Ireland, the Netherlands and Slovenia, which reported three compounds each.

The reported concentrations can be found at https://www.eea.europa.eu/data-and-maps/dashboards/air-quality-statistics-expert-viewer (accessed 18 July 2018).

([21]) The estimated reference level (0.12 ng/m^3) was estimated assuming WHO unit risk (WHO, 2010) for lung cancer for PAH mixtures and an acceptable risk of additional lifetime cancer risk of approximately 1 in 100 000 (ETC/ACM, 2011).
([22]) Malta submitted data on 26 July 2018, after the deadline for inclusion in the report had passed; see Box 1.1
([23]) BaP is a PAH found mainly in fine PM. The Ambient Air Quality Directive (EU, 2004) prescribes that BaP concentration measurements should be made in the PM_{10} fraction. Going beyond this requirement, data available for any PM fraction were used in the current analysis. The justification is that most of the BaP is present in $PM_{2.5}$, not in the coarser fraction of PM_{10}, and the gaseous fraction of the total BaP is quite small. On the one hand, this may introduce some systematic differences in the measured data, but, on the other hand, the inclusion of additional measured data allows a broader analysis of BaP levels across Europe. For more information, see discussion by ETC/ACM (2015b).
([24]) A data coverage of 14 %, as required by the Ambient Air Quality Directive (EU, 2004) for indicative measurements, was used as a minimum requirement for the analysis of BaP data.
([25]) Ten more French stations submitted valid data, which are not considered because of an internal problem in the Air Quality e-Reporting database.
([26]) All the other PAHs not included in this recommended list, but also reported by some countries, can be checked at https://www.eea.europa.eu/data-and-maps/dashboards/air-quality-statistics-expert-viewer (accessed 20 September 2018).
([27]) Two compounds were reported as measured as PM_{10} (air + aerosol).

Map 7.1 Concentrations of BaP, 2016

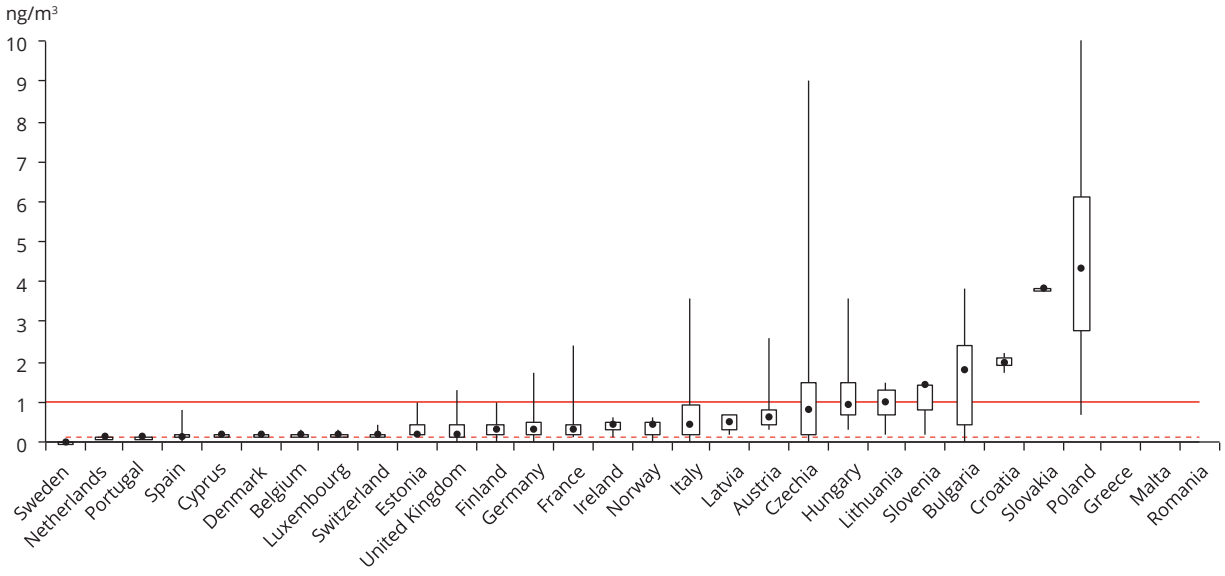


Notes: Observed concentrations of BaP in 2016. Dots in the first colour category correspond to concentrations under the estimated reference level (0.12 ng/m³, see Table 1.3). Dots in the last colour category correspond to concentrations exceeding the 2004 Ambient Air Quality Directive target value of 1 ng/m³.

Only stations reporting more than 14 % of valid data, as daily, weekly or monthly measurements, have been included in the map. The French overseas territories' stations are not shown in the map but can be found at https://www.eea.europa.eu/data-and-maps/dashboards/air-quality-statistics.

Source: EEA, 2018a.

Figure 7.1 BaP concentrations in 2016



Notes: The graph is based on the annual mean concentration values. For each country, the lowest, highest and median values (in ng/m³) recorded at its stations are given. The rectangles mark the 25th and 75th percentiles. At 25 % of the stations, levels are below the lower percentile; at 25 % of the stations, concentrations are above the upper percentile. The target value set by EU legislation is marked by the upper horizontal line. The estimated air-quality reference level is marked by the lower horizontal line. The graph should be read in relation to Map 7.1, as the country situation depends on the number of stations considered.

Source: EEA, 2018a.

8 Other pollutants: sulphur dioxide, carbon monoxide, benzene and toxic metals

8.1 European air quality standards and World Health Organization guidelines

Table 1.1 presents the European air quality standards for SO_2, CO, Pb, C_6H_6, As, Cd and Ni for health protection, as established in the Ambient Air Quality Directives (EU, 2004, 2008).

Table 1.3 shows the WHO AQGs for SO_2, CO, Cd and Pb and the reference levels for As, Ni and C_6H_6 ([28]).

The Ambient Air Quality Directive (EU, 2008) also sets standards for SO_2 for the protection of vegetation, shown in Table 1.2. The vegetation exposure to SO_2 levels above these standards is assessed in Section 11.4.

8.2 Status in concentrations

8.2.1 Sulphur dioxide

All EEA-39 countries (except Liechtenstein and Kosovo) plus Andorra reported measurements of SO_2 with data coverage over 75 % in 2016 from about 1 600 stations in total.

Except for five European countries (Bosnia and Herzegovina, Bulgaria, Norway, Serbia and Turkey), SO_2 concentrations are generally well below the limit values for the protection of human health, although exceedance of the WHO daily mean guideline persists.

In 2016, 17 stations ([29]) registered concentrations above the hourly limit value. And 23 stations ([30]) registered concentrations above the daily limit value for SO_2.

On the contrary, 37 % of all the stations reporting SO_2 levels, located in 30 reporting countries ([31]), measured SO_2 concentrations above the WHO air quality guideline of 20 µg/m³ for daily mean concentrations in 2016.

8.2.2 Carbon monoxide

The highest CO levels are found in urban areas, typically during rush hour, or downwind from large industrial emission sources. All EEA-39 countries (except Iceland, Kosovo and Liechtenstein), plus Andorra, reported CO data from 874 operational stations with more than 75 % of valid data. Only five stations registered concentrations above the CO limit value and the WHO AQG value in 2016: one suburban background station in Albania; two urban traffic stations and one urban industrial station in the former Yugoslav Republic of Macedonia; and one urban traffic station in Sweden (Map 8.1).

When concentrations are below the 'lower assessment threshold' (LAT), air quality can be assessed by means of only modelling or objective estimates. At 93 % of locations, maximum daily 8-hour mean concentrations of CO were below the LAT of 5 mg/m³ in 2016 (first two categories of coloured dots in Map 8.1).

8.2.3 Benzene

C_6H_6 measurements in 2016 with at least 50 % data coverage were reported from 724 stations in 31 European countries (all EU-28 and Albania, Norway and Switzerland).

Only four stations measured concentrations above 5.0 µg/m³, all in urban areas: two background stations in Poland; one traffic station in Greece; and one industrial station in France. At 90 % of locations, annual mean concentrations of C_6H_6 were below the LAT of 2 µg/m³ in 2016 (first two categories of coloured dots in Map 8.2)

([28]) As the WHO has not provided a guideline for As, Ni or C_6H_6, the reference levels presented in Table 3.2 were estimated assuming the WHO unit risk for cancer and an acceptable risk of additional lifetime cancer risk of approximately 1 in 100 000 (ETC/ACM, 2011).
([29]) Eight in Turkey, four in Bosnia and Herzegovina, three in Serbia, one in Bulgaria and one in Norway.
([30]) In Turkey (14), Bosnia and Herzegovina (three), Serbia (three), Norway (two) and Bulgaria (one).
([31]) All, except Andorra, Cyprus, Denmark, Latvia, Luxembourg, Malta, Montenegro and Switzerland.

Regarding the estimated WHO reference level (Table 1.3), 15 % of all stations reported concentrations above this reference level in 2016, distributed across 16 European countries ([32]) (Map 8.2).

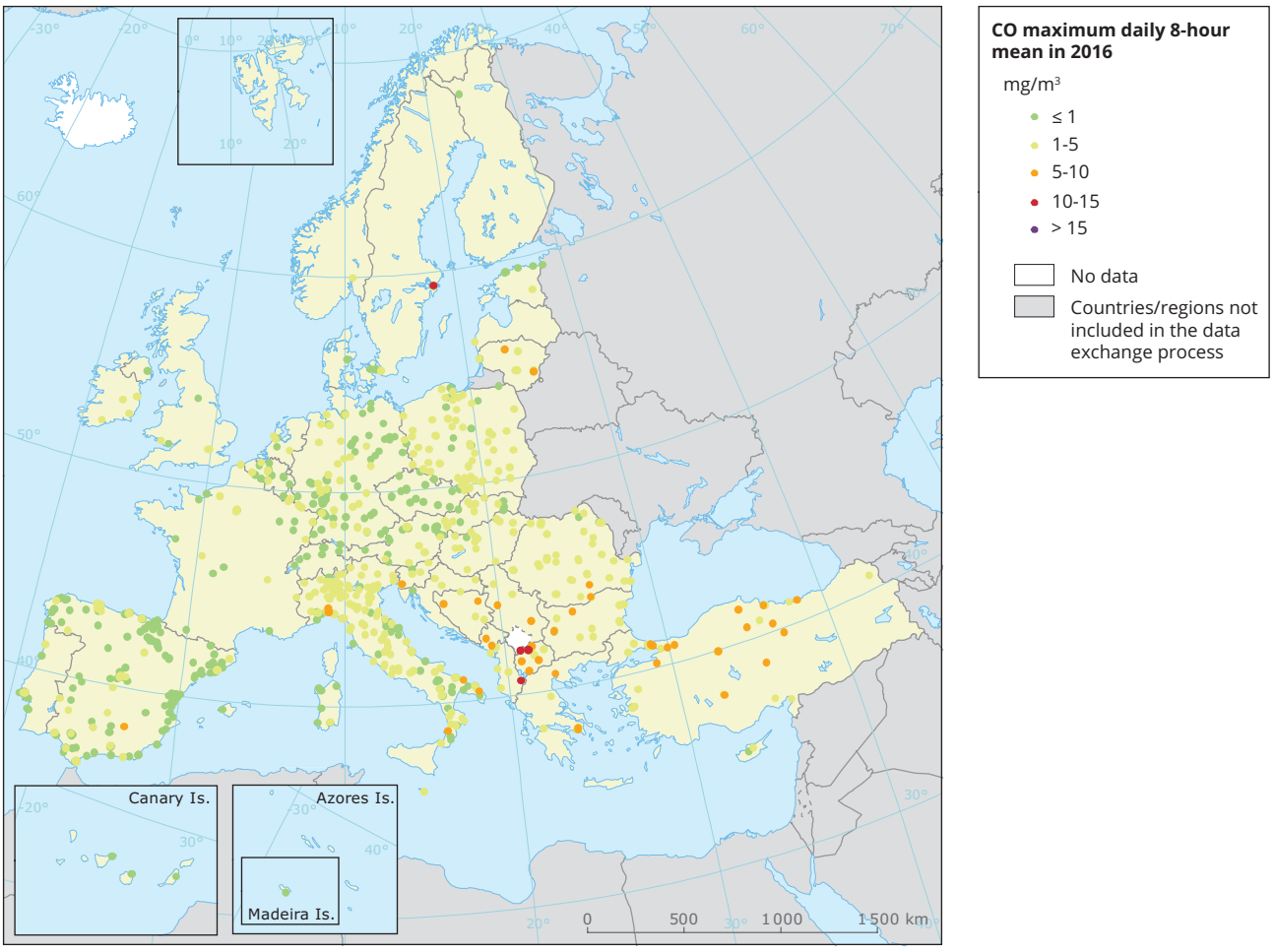
8.2.4 Toxic metals

Monitoring data for toxic metals are missing for parts of Europe. This is probably because concentrations are generally low and below the LAT, allowing assessment to be made by modelling or objective estimates. In 2016, between 647 and 698 stations reported measurement data for each toxic metal (As, Cd, Pb and Ni), with a minimum data coverage of 14 %.

The air pollution problems caused by the toxic metals As, Cd, Pb and Ni in terms of ambient air concentrations are highly localised, as can be seen in Maps 8.3 and 8.4. This is because problems are typically related to specific industrial plants. The results from the 2016 data reported can be summarised as follows:

- Data for As from 678 stations in 28 European countries ([33]) were reported in 2016. Seven stations reported concentrations above the target value (6 ng/m³) in both industrial and background urban areas in Belgium (five) and Poland (two). Concentrations of As below the LAT (2.4 ng/m³) were reported at 94 % of the stations in 2016 (see Map 8.3).

Map 8.1 Concentrations of CO, 2016

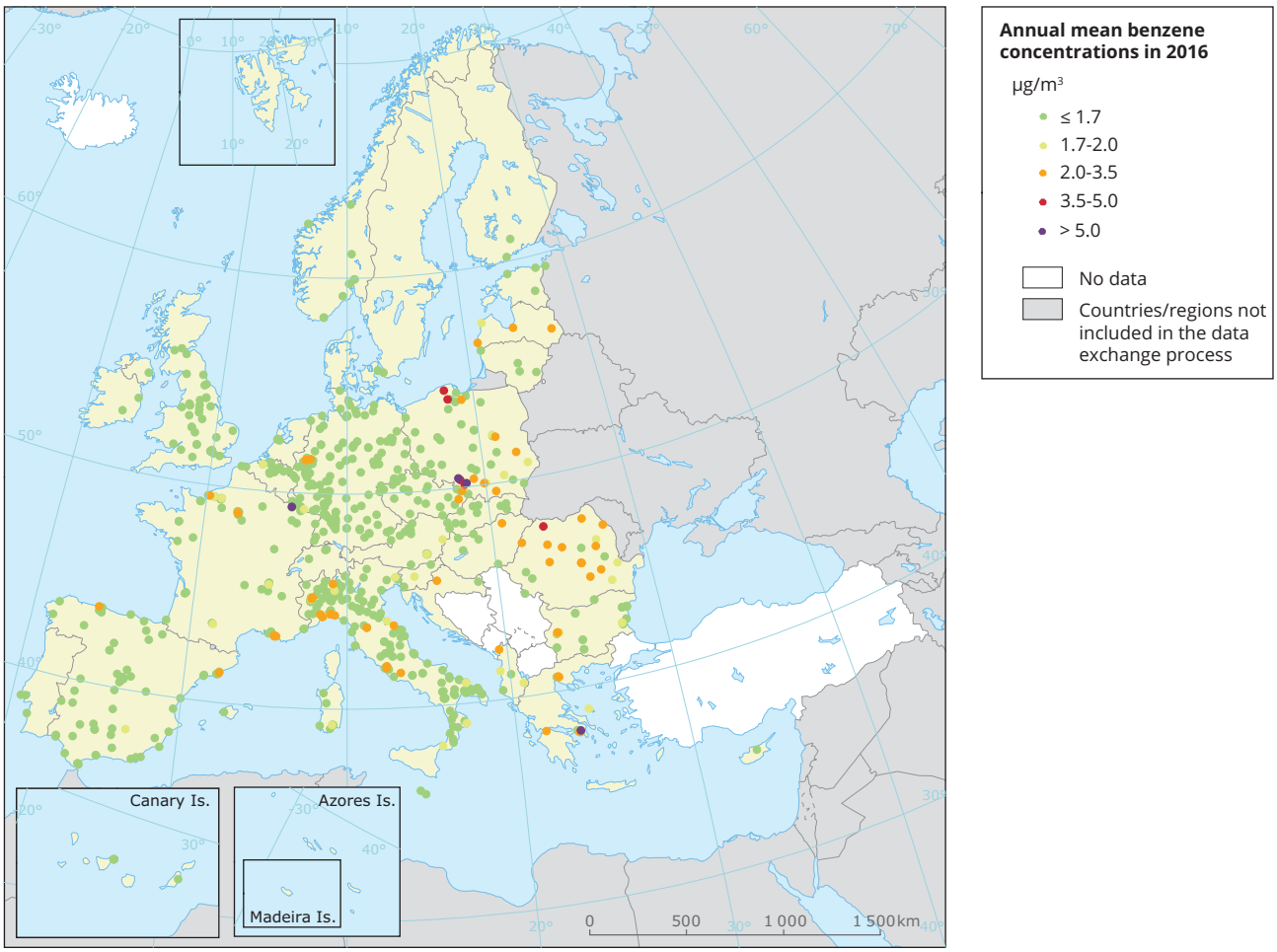


Notes: Observed concentrations of CO in 2016. The map shows the CO maximum daily 8-hour mean. Dots in the last two colour categories correspond to values above the EU annual limit value and the WHO AQG (10 mg/m³). Only stations with more than 75 % of valid data have been included in the map.

Source: EEA, 2018a.

([32]) In Albania, Austria, Belgium, Bulgaria, Croatia, Czechia, France, Germany, Greece, Hungary, Italy, Latvia, Poland, Romania, Slovenia and Spain.
([33]) 25 Member States (all EU-28, except Estonia, Greece and Malta, which submitted data on 26 July 2018, once the deadline for inclusion in the report had passed; see Box 1.1), Norway, Serbia and Switzerland.

Map 8.2 Concentrations of C_6H_6, 2016



Notes: Observed concentrations of C_6H_6 in 2016. Dots in the last colour category correspond to concentrations above the limit value of 5 µg/m³. Dots in the first colour category correspond to concentrations under the estimated WHO reference level (1.7 µg/m³, see Table 1.3). Only stations reporting more than 50 % of valid data have been included in the map. The French overseas territories' stations are not shown in the map but can be found at https://www.eea.europa.eu/data-and-maps/dashboards/air-quality-statistics.

Source: EEA, 2018a.

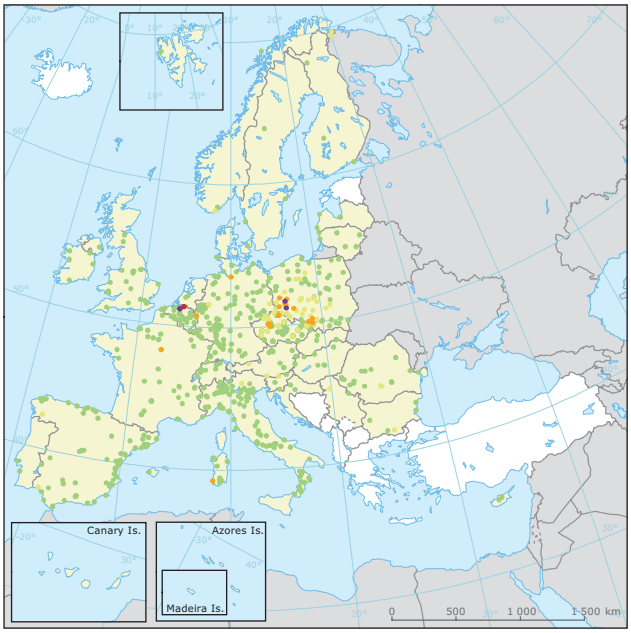
- Cd data from 698 stations in 28 European countries ([34]) were reported in 2016. Concentrations above the target value (5 ng/m³) were measured at three stations in 2016, in suburban areas, either industrial (Belgium, two stations) or background (Slovenia, one station). At the great majority of stations (97 %), Cd concentrations were below the LAT (2 ng/m³) (see Map 8.3).

- Pb data from 647 stations in 26 European countries ([35]) were reported in 2016. No stations reported Pb concentrations above the 0.5 µg/m³ limit value. About 99 % of the stations reported Pb concentrations below the LAT of 0.25 µg/m³ (see Map 8.4)

- Ni data from 679 stations in 28 European countries ([36]) were reported in 2016. Concentrations were above the target value of 20 ng/m³ at five stations in the United Kingdom (two), Norway (one), France (one) and Italy (one). Except for one urban background station in the United Kingdom, the other four were industrial stations. About 97 % of the stations reported Ni concentrations below the LAT of 10 ng/m³ (see Map 8.4)

([34]) 25 Member States (all EU-28, except Estonia, Greece and Malta, which submitted data on 26 July 2018, once the deadline for inclusion in the report had passed; see Box 1.1), Norway, Serbia and Switzerland.
([35]) 24 Member States (all EU-28, except Estonia, Greece, Hungary and Malta, which submitted data on 26 July 2018, once the deadline for inclusion in the report had passed; see Box 1.1), Serbia and Switzerland.
([36]) 25 Member States (all EU-28, except Estonia, Greece and Malta, which submitted data on 26 July 2018, once the deadline for inclusion in the report had passed; see Box 1.1), Norway, Serbia and Switzerland.

Map 8.3 Concentrations of As and Cd, 2016



Annual mean arsenic concentrations in 2016

ng/m³ ≤ 1 1-3 3-6 6-9 > 9

No data

Countries/regions not included in the data exchange process

Annual mean cadmium concentrations in 2016

ng/m³ ≤ 1 1-2 2-5 5-8 > 8

No data

Countries/regions not included in the data exchange process

Notes: The maps show the corresponding annual mean concentrations for As and Cd. Dots in the last two colour categories correspond to concentrations above the target values as presented in Table 1.1 Only stations reporting more than 14 % of valid data have been included in the maps. The French overseas territories' stations are not shown in the maps but can be found at https://www.eea.europa.eu/data-and-maps/dashboards/air-quality-statistics.

Source: EEA, 2018a.

- Hg concentrations recorded in the Air Quality e-Reporting Database are very sparse. The Ambient Air Quality Directive (EU, 2004) does not set any standard for Hg, but calls on EU Member States to perform (indicative) measurements of total gaseous Hg at one background station at least. Reported concentrations of Hg in 2016 were very low.

  In 2013, governments worldwide agreed to a global, legally binding treaty to prevent emissions and releases of Hg. The Minamata Convention on Mercury (UN, 2013) for the reduction of Hg emissions and exposure entered into force on 18 May 2017, when the EU, together with several Member States, ratified it. As a result, it is expected that European monitoring of Hg in the atmosphere will be strengthened.

  In addition to reporting the concentration of toxic metals in ambient air, several countries also measure and report yearly their deposition onto the ground, usually in rural background areas. The reported data can be found at https://www.eea.europa.eu/data-and-maps/dashboards/air-quality-statistics-expert-viewer (accessed 18 July 2018).

Map 8.4 Concentrations of Pb and Ni, 2016

Annual mean lead concentrations in 2016

µg/m³ ≤ 0.02 | 0.02-0.10 | 0.10-0.50 | 0.50-1.00 | > 1.00

No data

Countries/regions not included in the data exchange process

Annual mean nickel concentrations in 2016

ng/m³ ≤ 5 | 5-10 | 10-20 | 20-30 | > 30

No data

Countries/regions not included in the data exchange process

Notes: The maps show the corresponding annual mean concentrations for Pb and Ni. Dots in the last two colour categories correspond to concentrations above the limit or target values as presented in Table 1.1. Only stations reporting more than 14 % of valid data have been included in the maps. The French overseas territories' stations are not shown in the maps but can be found at https://www.eea.europa.eu/data-and-maps/dashboards/air-quality-statistics

Source: EEA, 2018a.

Photo: © Agnieszka Hejmanowska, WaterPIX-EEA

9 Population exposure to air pollutants

Health effects are related to both short- (over a few hours or days) and long-term (over months or years) exposure to air pollution. The Ambient Air Quality Directives and WHO define, respectively, air quality standards and guidelines for the protection of human health from both short- and long-term effects, depending on the pollutant and its effects on health (see Tables 1.1 and 1.3, respectively). These values differ and the WHO guidelines are generally stricter (for NO_2 both the annual limit value and the long-term guideline are the same). The WHO guidelines are designed to offer guidance in reducing the health impacts of air pollution and are based on expert evaluation of current scientific evidence. The EU standards are a political compromise that also takes into account what is economically feasible.

9.1 Exposure of the EU-28 population in urban and suburban areas in 2016

The monitoring data reported by the EU-28 (EEA, 2018a) provide the basis for estimating the exposure of the urban population ([37]) to exceedances of the most stringent European air quality standards and WHO AQG. The exposure is estimated based upon measured concentrations at all urban and suburban background monitoring stations for most of the urban population, and at traffic stations for populations living within 100 m of major roads. The methodology is described by the EEA (2018f).

Table ES.1 shows the minimum and maximum percentage of the EU-28 urban population exposed to concentrations above certain EU limit or target values and WHO AQG levels (or an estimated reference level where no WHO AQG level exists) between 2014 and 2016. The ranges reflect, apart from changes in concentrations, variations attributable to meteorology and changes in the subset of cities and stations included in the year-to-year estimates.

In 2016, the proportion of the EU-28 urban population exposed to PM_{10} and $PM_{2.5}$ levels above limit values and WHO guidelines was the lowest since 2000, showing a decreasing trend in the percentage of urban population exposed to PM concentrations above standards and WHO guidelines since 2000 (2006 for $PM_{2.5}$, as a result of poor coverage of monitoring stations before that date) (EEA, 2018f).

About 13 % of the EU-28 urban population was exposed to **PM_{10}** above the EU daily limit value. The extent of exposure above this EU daily limit value fluctuated between 13 % and 42 % over the period 2000-2016, with 2003 the year with the highest extent of exposure. Furthermore, 42 % of the same urban population was exposed to concentrations exceeding the stricter WHO AQG value for PM_{10} in 2016. The percentage of the urban population exposed to levels above the WHO annual AQG (20 µg/m^3) ranged between 42 % and 91 % (maximum also reached in 2003) in the period 2000-2016.

About 6 % of the EU-28 urban population was exposed to **$PM_{2.5}$** above the EU limit value in 2016. The percentage was in the range of 6-17 % in 2006-2016. The urban population's exposure to levels above the more stringent WHO AQG for $PM_{2.5}$ decreased to 74 % in 2016 from the initial maximum of 97 % in 2006.

In 2016, about 12 % of the EU-28 population in urban areas was exposed to **O_3** concentrations above the EU target value threshold, which is a considerable decrease compared to the high exposure of 2015 (30 %), but higher than in 2014 (where the minimum of 7 % was reached). The percentage of the urban population exposed to O_3 levels above the target value threshold has fluctuated between 7 % and 55 % since 2000. The percentage of the EU-28 urban population exposed to O_3 levels exceeding the WHO AQG value remains very high and has fluctuated between 94 % and 99 % since 2000. In 2016, as much as

([37]) The number of rural stations is too low and/or spatially not representative to estimate the exposure of the rural population.

around 98 % of the total EU-28 urban population was exposed to O_3 levels exceeding the WHO AQG.

About 7 % of the EU-28 urban population was exposed to **NO_2** concentrations above the EU annual limit value and the WHO AQG value in 2016. The percentage of the urban population exposed to concentrations above the annual limit value has gradually decreased since the maximum of 31 % in 2003 and has stabilised between 7 % and 9 % over the 5-years period 2012-2016.

In 2016, 21 % of the urban population in the EU-28 was exposed to **BaP** annual concentrations above the EU target value (1.0 ng/m^3) and 90 % was exposed to concentrations above the estimated reference level (0.12 ng/m^3 as annual mean). Since 2008, there has been no significant change in the extent of the urban population exposed to high BaP concentrations. Between 17 % and 24 % of the EU-28 urban population was exposed to BaP concentrations above the target value in 2008-2016, whereas 81-91 % of the EU-28 urban population was exposed to BaP concentrations above the estimated reference level over the same period (Table ES.1).

Exposure to **SO_2** has decreased over the past few decades and, since 2007, the exposure of the urban population to concentrations above the EU daily limit value has remained under 0.5 %. The EU-28 urban population exposed to SO_2 levels exceeding the WHO AQG decreased from 85 % of the total urban population in 2010 to 23 % in 2016 (Table ES.1).

Based on the available measurements for 2016 and previous years, it can be concluded that the European population's exposure to **CO** ambient concentrations above the EU limit value is very localised and infrequent (see Section 8.2.2).

Exposure in Europe to **C_6H_6** concentrations above the EU limit value is limited to a few localised areas with higher concentrations, which are often close to traffic or industrial sources. Concentrations above the estimated WHO reference level are more current and widespread (see Section 8.2.3).

Human exposure to **As, Cd, Pb** and **Ni** ambient air concentrations above the EU limit or target values is restricted to a few areas in Europe and is typically caused by specific industrial or energy plants. However, atmospheric deposition of toxic metals contributes to the exposure of ecosystems and organisms to toxic metals and to bioaccumulation and biomagnification in the food chain, affecting human health.

9.2 Exposure of total European population in 2015 and changes over time

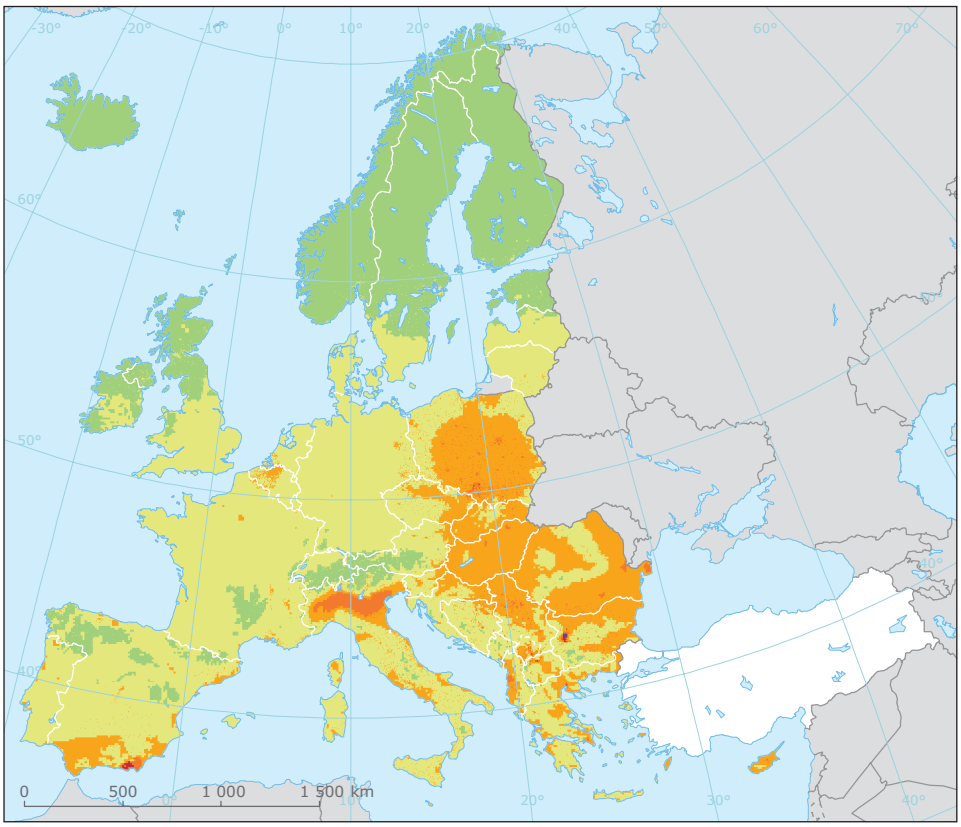
To estimate the exposure of the total European population ([38]) to the different pollutant standards, an interpolation of annual statistics of reported monitoring data from 2015 is used. It combines the monitoring data from rural and urban background stations (and traffic stations in the case of NO_2, to take into account hotspots, since traffic is the most important source of NO_2) with results from the EMEP chemical transport model ([39]) and other supplementary data (such as altitude and meteorology) (for further details, see ETC/ACM, 2017b, 2018b). The maps of spatially interpolated air pollutant concentrations (annual mean concentration for PM_{10}, $PM_{2.5}$ and NO_2, and accumulated O_3 concentration (8-hour daily maximum) in excess of 35 ppb (SOMO35) for O_3) are presented in Figure 9.1. The population exposure is estimated by combining these concentration maps with the population density (based on the GEOSTAT 2011 grid dataset; Eurostat, 2014), which is the basis for the health impact assessment estimates presented in Chapter 10 ([40]).

Figure 9.2 shows the European population frequency distribution for each exposure class in 2015. About 46 % of the European population (and 45 % of the EU-28 population) was exposed in 2015 to PM_{10} annual average concentrations above the WHO AQG (bars to the right of the dotted line at 20 µg/m^3 in Figure 9.2a). The population exposure exceeding the EU limit value (bars to the right of the continuous line at 40 µg/m^3 in Figure 9.2a) was about 0.5 % for the population of the total European area considered and the EU-28.

When it comes to $PM_{2.5}$, almost 81 % of the population of the total European area considered and of the EU-28 were exposed in 2015 to annual mean concentrations above the WHO AQG (bars to the right of the dotted line at 10 µg/m^3 in Figure 9.2b) and 6 % to concentrations above the EU limit value (bars to the right of the continuous line at 25 µg/m^3 in Figure 9.2b).

([38]) All European countries (not only EU-28) and all populations (not only urban).
([39]) At the time of drafting this report, the most up-to-date data from the EMEP model were from 2015, that is why exposure of total population is calculated for 2015 and not for 2016 as in the case of urban population (Section 9.1).
([40]) More detailed information on population exposure to $PM_{2.5}$, NO_2 and O_3 at country level can be found in tables 3.1, 5.1 and 4.2 in ETC/ACM (2018b).

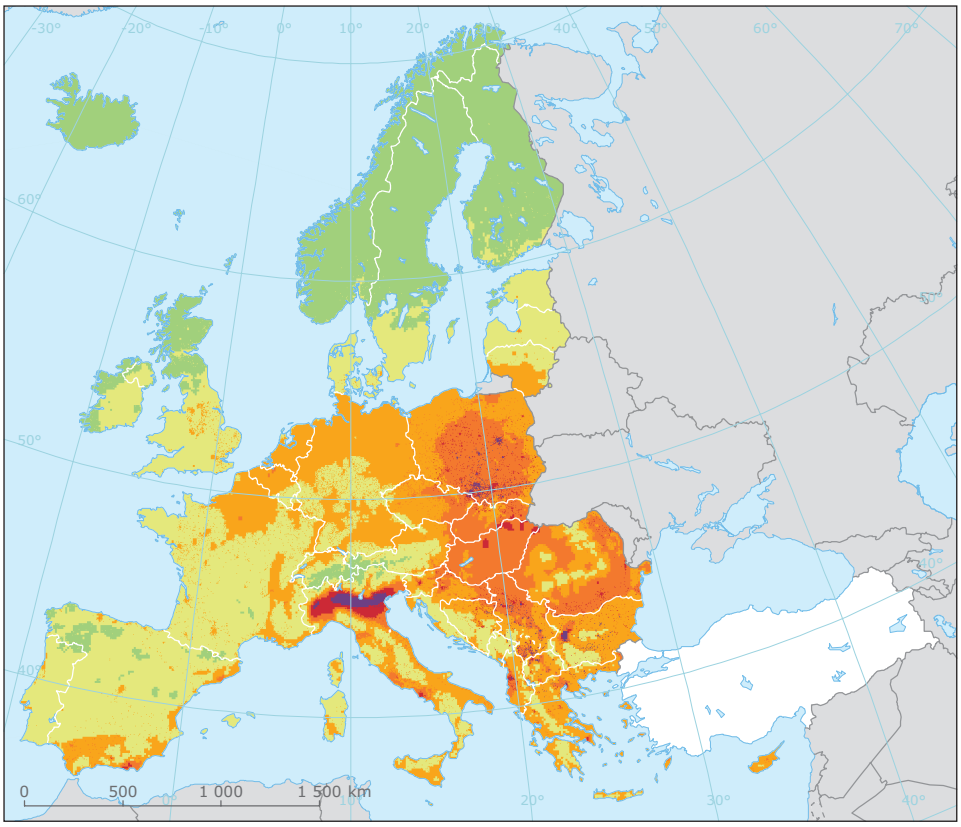
Figure 9.1 **Concentration interpolated maps of PM_{10} (annual mean, µg/m³), $PM_{2.5}$ (annual mean, µg/m³), NO_2 (annual mean, µg/m³), and O_3 (SOMO35, µg/m³.days) for the year 2015**



PM_{10} annual mean in 2015

µg/m³

- ≤ 10
- 10-20
- 20-30
- 30-40
- 40-50
- > 50
- No available data
- Countries/regions not included in the data exchange process

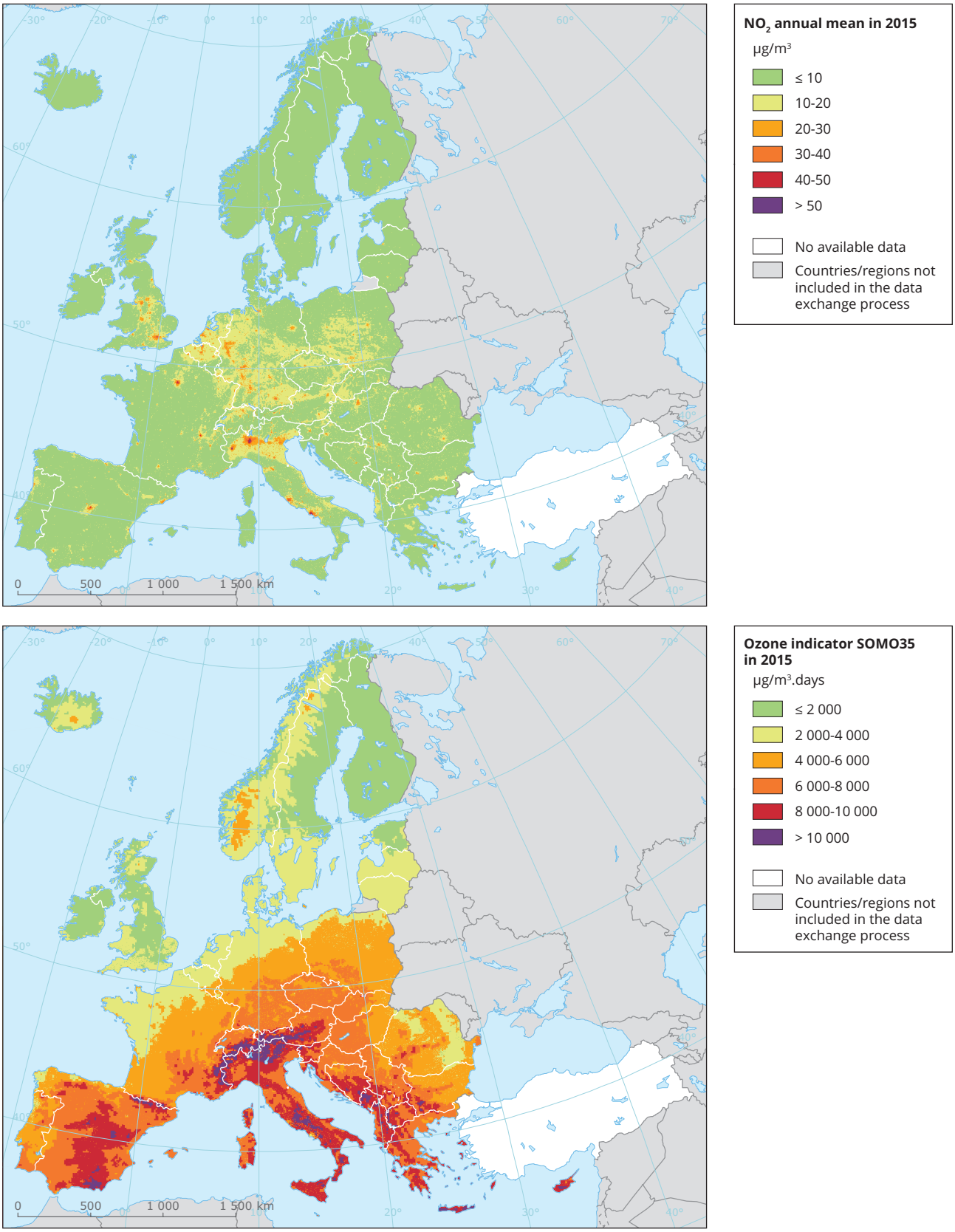


$PM_{2.5}$ annual mean in 2015

µg/m³

- ≤ 5
- 5-10
- 10-15
- 15-20
- 20-25
- > 25
- No available data
- Countries/regions not included in the data exchange process

Figure 9.1 Concentration interpolated maps of PM_{10} (annual mean, µg/m³), $PM_{2.5}$ (annual mean, µg/m³), NO_2 (annual mean, µg/m³), and O_3 (SOMO35, µg/m³.days) for the year 2015 (cont.)

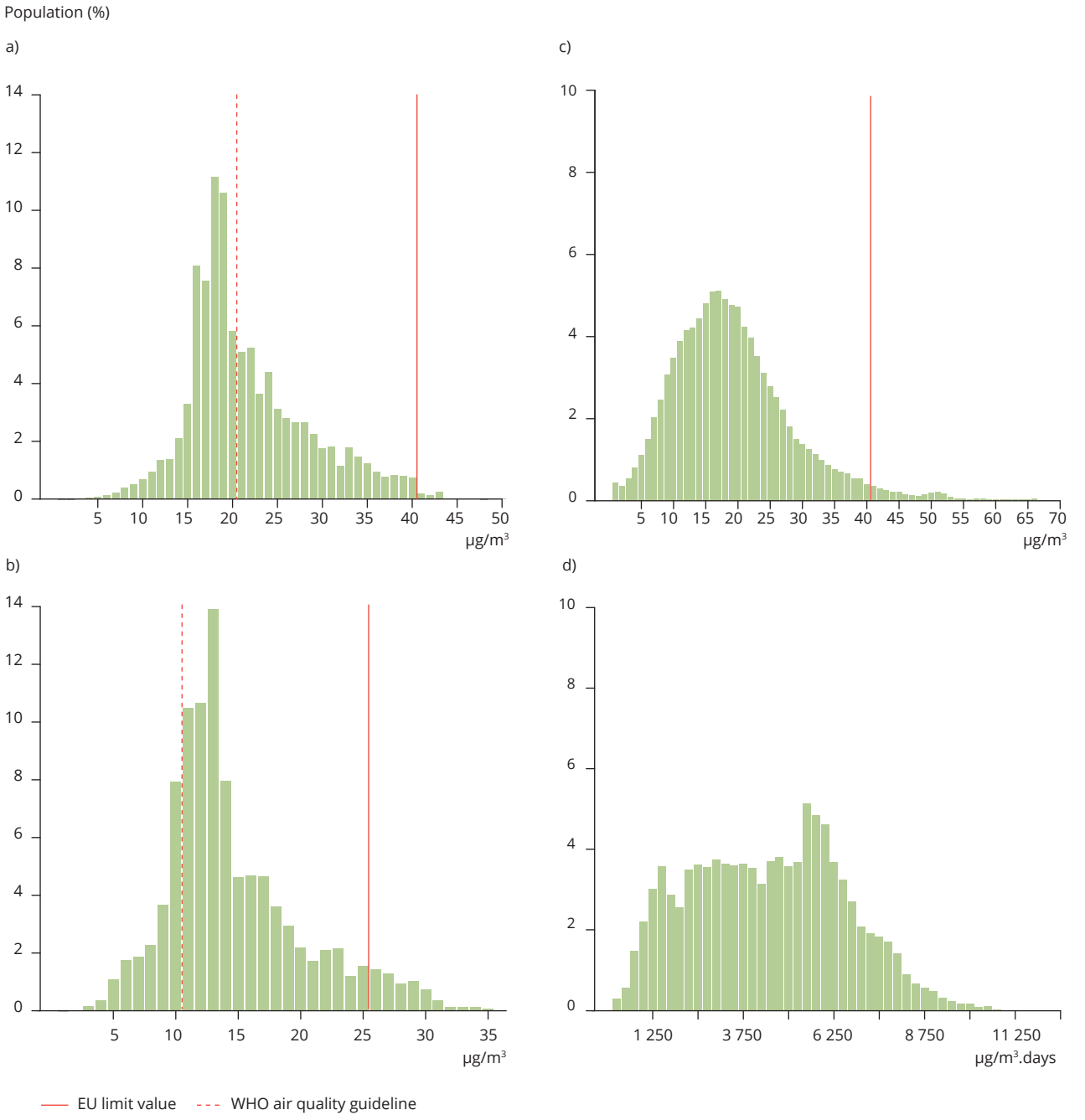


Source: ETC/ACM, 2018b.

For NO_2, it has been estimated that, in 2015, about 3 % of the European and EU-28 populations lived in areas with annual average concentrations above the EU limit value (see bars to the right of the continuous line at 40 µg/m³ in Figure 9.2c). It should be mentioned that, in contrast to the other pollutants, the NO_2 mapping methodology incorporates monitoring data from not only the rural and urban background stations but also traffic locations (ETC/ACM, 2017b).

Finally, for O_3 (Figure 9.2d) it has been estimated that, in 2015, about 22 % of the European population lived in

Figure 9.2 **Frequency distribution of the total population exposure to (a) PM_{10} (annual mean), (b) $PM_{2.5}$ (annual mean), (c) NO_2 (annual mean) and (d) O_3 (SOMO35) in 2015**



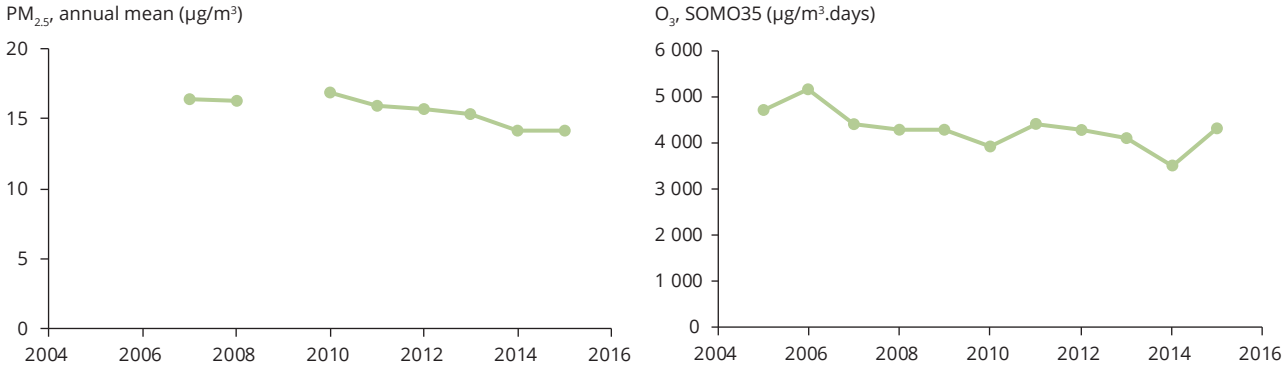
Source: ETC/ACM, 2018b.

areas with SOMO35 values above 6 000 µg/m³.days ([41]). This corresponds to the fifth lowest level in the 11-year period 2005-2015 (ETC/ACM, 2018b).

Since 2005 and 2007, the maps for O_3 and $PM_{2.5}$ (no map in 2009), respectively, have been prepared in a consistent way. This enables an analysis of changes in total European population exposure over time (Figure 9.3). The $PM_{2.5}$ annual mean concentrations show a steady decrease of about 0.3 µg/m³ per year. For the O_3 concentration (expressed as SOMO35), a small decreasing trend is also observed in spite of year-to-year variability.

Although the spatial distributions of PM, NO_2 and O_3 concentrations differ widely, the possibility of an accumulation of risks resulting from high exposures to all three pollutants cannot be excluded. The three most frequently exceeded EU standards are PM_{10} daily limit value, NO_2 annual limit value and O_3 target value (see ETC/ACM, 2018b). Combining the maps for those three standards shows that, of the total population of 536 million in the model area, 8.9 % (47.5 million) live in areas where two or three of those air quality standards are exceeded; and 3.9 million people live in areas where all three standards are exceeded. It should be noted that the majority of them (3.7 million inhabitants) live in northern Italy.

Figure 9.3 Changes in total European population exposure to $PM_{2.5}$ (annual mean) and ozone (SOMO35)



Note: Exposure expressed as population averaged concentrations.

Source: ETC/ACM, 2018b.

([41]) The comparison of the 93.2 percentile of maximum daily 8-hour means with the SOMO35 results for all background stations shows that there is no simple relation between the two indicators; however, it seems that the O_3 target value threshold (120 µg/m³) is related to some extent to SOMO35 in the range 6 000-8 000 µg/m³ .days (ETC/ACM, 2017a).

10 Health impacts of exposure to fine particulate matter, ozone and nitrogen dioxide

It is well documented that exposure to air pollution may lead to adverse health effects, such as premature mortality and morbidity, mainly related to respiratory and cardiovascular diseases. The health impacts of air pollution can therefore be quantified and expressed as estimates of premature mortality and morbidity. Mortality reflects reduction in life expectancy owing to premature death as a result of air pollution exposure, whereas morbidity relates to the occurrence of illness and years lived with a disease or disability, ranging from subclinical effects (e.g. inflammation) and symptoms such as coughing to chronic conditions that may require hospitalisation. Even less severe effects might have strong public health implications, because air pollution affects the whole population on a daily basis.

Most of the evidence on the health impacts attributable to exposure to ambient air pollution tends to focus on all-cause, as well as on cause-specific (in particular respiratory, cardiovascular and lung cancer), premature mortality and morbidity (WHO, 2006b, 2008, 2013a). There is growing evidence, however, that exposure may lead to a range of other effects (see Section 1.3.1). A number of studies (e.g. Amann, 2014) also show that, after monetising the health effects, the total external costs caused by mortality outweigh those arising from morbidity. In this report, the focus is, as in previous years, on estimating the premature mortality related to air pollution, focusing on PM, NO_2 and O_3. Exposure to other air pollutants, such as benzene or PAH (in particular, BaP), also has strong health impacts; however, under the current European air quality conditions, their impact on the total air pollution-related mortality is small compared with PM, NO_2 and O_3, and may, in part, be already included in estimates of the effects of PM.

10.1 Methodology used to assess health impacts

The health impacts from air pollution can be estimated using different health metrics; in this report, mortality endpoints (Box 10.1) are presented. In fact, the impacts estimated are those attributable to exposure to $PM_{2.5}$, NO_2 and O_3 in Europe for 2015 ([42]). This assessment required information on air pollution, demographic data and the relationship between exposure to ambient pollutant concentrations and a health outcome. The maps of air pollutant concentrations used in the assessment are those presented in Section 9.2 (annual mean concentration for $PM_{2.5}$ and NO_2, and SOMO35 for O_3; see Figure 9.1). The demographic data and the health-related data were taken from Eurostat (2018d) and WHO (2017b), respectively. The exposure-response relation and the population at risk have been selected in accordance with the recommendation given by the Health Risks of Air Pollution in Europe (HRAPIE) project (WHO, 2013a). So, for $PM_{2.5}$, all-cause (natural) mortality is considered in ages above 30, for all concentrations, assuming an increase in the risk of mortality of 6.2 % for a 10 µg/m^3 increase of $PM_{2.5}$. For NO_2, all-cause (natural) mortality is considered in ages above 30, for concentrations above 20 µg/m^3, assuming an increase in the risk of mortality of 5.5 % for a 10 µg/m^3 increase of NO_2. And, finally, for O_3, all-cause (natural) mortality is considered for all ages assuming an increase in the risk of mortality of 0.29 % per 10 µg/m^3 increase of SOMO35 ([43]).

The impacts estimated for the different pollutants cannot be simply added to determine the estimated total health impact attributable to exposure. For example, as concentrations of $PM_{2.5}$ and NO_2 are

([42]) In the methodology used, the air pollutant concentrations are obtained from interpolated maps (see Section 9.2 and Figure 9.1). To produce these maps, information from the EMEP model is needed and, at the time of drafting this report, the most up-to-date data from the EMEP model were from 2015 (ETC/ACM, 2018b).

([43]) In 2017, a sensitivity analysis was performed using different concentrations above which to consider the health impacts (EEA, 2017a), namely the effects from 2.5 µg/m^3 of $PM_{2.5}$ and from 10 µg/m^3 of NO_2. The results of a similar analysis are shown this year in Annex 1.

(sometimes strongly) correlated, the impacts estimated for these cannot be aggregated. Doing so may lead to double counting of up to 30 % of the effects of NO_2 (WHO, 2013a).

A further description and details of the methodology are given in ETC/ACM (2016) and can also be found in EEA (2017a).

10.2 Health impact assessment results

The results of the health impact assessment are presented in Tables 10.1 and 10.2 for 41 European countries individually, for the 41 countries as a whole and for the EU-28. Table 10.1 presents for each pollutant, the population-weighted concentration and the estimated number of attributable premature deaths for 2015.

In the 41 countries listed, 422 000 premature deaths are attributed to $PM_{2.5}$ exposure; 79 000 premature deaths are attributed to NO_2; and 17 700 premature deaths to O_3 exposure. In the EU-28, the premature deaths attributed to $PM_{2.5}$, NO_2 and O_3 exposure are 391 000, 76 000, and 16 400, respectively. In line with the small variations in concentrations, the estimated numbers attributable to $PM_{2.5}$ are slightly lower than estimated for 2014, and those attributed to NO_2 slightly higher. The population-weighted O_3 concentration increased from 3 500 to 4 300 ($\mu g/m^3$). day; a corresponding increase in health impacts has been found. However, the health impacts attributable to O_3 remain relatively small compared with those caused by the other pollutants.

Table 10.2 presents the estimated number of YLL and the YLL per 100 000 inhabitants because of exposure to $PM_{2.5}$, NO_2 and O_3 for 2015. In total, in the 41 countries assessed, 4 466 000 YLL are attributed to $PM_{2.5}$ exposure, 821 000 to NO_2 exposure, and 193 800 to O_3 exposure. In the EU-28, the YLL attributed to $PM_{2.5}$, NO_2 and O_3 exposure are 4 150 000, 795 000 and 180 000, respectively.

The largest contribution to the uncertainties in the estimates of premature deaths and YLL is related to the choice of the relative risk coefficients. In the results presented below, and in Annex 1, the uncertainty intervals are not explicitly given; uncertainties in health outcomes (expressed as 95 % confidence intervals ([44])) are estimated as ±35 % ($PM_{2.5}$), ±45 % (NO_2) and ±50 % (O_3).

For $PM_{2.5}$, the highest numbers of premature deaths and YLL are estimated for the countries with the largest populations (Germany, Italy, Poland, France and the United Kingdom). However, in relative terms, when considering YLL per 100 000 inhabitants, the largest impacts are observed in central and eastern European countries where the highest concentrations are also observed, i.e. Kosovo, Bulgaria, Serbia, the former Yugoslav Republic of Macedonia and Hungary. The lowest relative impacts are found in the countries at the northern and north-western edges of Europe: Iceland, Norway, Ireland, Sweden and Finland.

The largest health impacts attributable to NO_2 exposure are seen in Italy, Germany, France, the United Kingdom and Spain. When considering YLL per 100 000 inhabitants, the highest rates are found in Italy, Greece, Spain, France and Germany.

Regarding O_3, the countries with the largest impacts are Italy, Germany, France, Spain and Poland; and the countries with the highest rates of YLL per 100 000 inhabitants are Kosovo, Montenegro, Hungary, Serbia and Greece.

Box 10.1

Premature deaths are deaths that occur before a person reaches an expected age. This expected age is typically the life expectancy for a country stratified by sex. Premature deaths are considered to be preventable if their cause can be eliminated.

Years of life lost (YLL) are defined as the years of potential life lost due to premature death. It is an estimate of the average number of years that a person would have lived if he or she had not died prematurely. YLL takes into account the age at which deaths occur and is greater for deaths at a younger age and lower for deaths at an older age. It gives, therefore, more nuanced information than the number of premature deaths alone.

([44]) The confidence intervals (CIs) give the upper and lower boundaries of the 95 % confidence interval of the estimate, taking into account only the uncertainty in the relative risk. The CIs are: for $PM_{2.5}$, 4.0-8.3 %; for NO_2, 3.1-8.0 %; and for O_3, 0.14-0.43 %.

Table 10.1 Premature deaths attributable to $PM_{2.5}$, NO_2 and O_3 exposure in 41 European countries and the EU-28, 2015

		$PM_{2.5}$		NO_2		O_3	
Country	**Population (1 000)**	**Annual mean [a]**	**Premature deaths [b]**	**Annual mean [a]**	**Premature deaths [b]**	**SOMO35 [a]**	**Premature deaths [b]**
Austria	8 576	13.3	5 900	19.8	1 200	6 170	380
Belgium	11 237	13.0	7 400	20.9	1 500	2 790	220
Bulgaria	7 202	24.1	14 200	16.1	640	4 180	350
Croatia	4 225	17.4	4 500	17.3	430	6 240	230
Cyprus	1 173	16.9	750	14.1	30	6 390	40
Czechia	10 538	17.0	10 100	16.6	490	5 560	460
Denmark	5 660	9.7	2 800	10.5	80	2 200	90
Estonia	1 315	6.7	560	8.2	< 5	1 780	20
Finland	5 472	5.3	1 500	8.8	40	1 360	50
France	66 488	11.9	35 800	17.9	9 700	4 250	1 800
Germany	81 198	12.3	62 300	20.0	13 100	4 300	3 000
Greece	10 858	19.1	12 000	18.1	2 300	6 910	610
Hungary	9 856	18.9	12 800	18.0	1 300	5 550	530
Ireland	4 629	6.5	1 100	7.6	30	860	20
Italy	60 796	18.5	60 600	24.9	20 500	6 860	3 200
Latvia	1 986	10.6	1 600	12.1	130	2 560	50
Lithuania	2 921	11.7	2 600	12.2	70	2 800	90
Luxembourg	563	12.0	240	19.9	50	3 460	10
Malta	429	12.8	240	16.5	20	5 790	10
Netherlands	16 901	12.3	9 800	20.5	1 900	2 680	290
Poland	38 006	21.6	44 500	15.6	1 700	4 530	1 300
Portugal	9 870	9.8	5 500	15.7	890	3 990	300
Romania	19 871	18.1	25 400	14.9	1 300	2 950	580
Slovakia	5 421	19.1	5 200	16.9	240	5 460	210
Slovenia	2 063	17.4	1 800	16.7	160	6 650	100
Spain	44 154	12.7	27 900	21.2	8 900	5 820	1 800
Sweden	9 747	5.9	3 000	10.8	110	2 080	140
United Kingdom	64 875	9.4	31 300	19.7	9 600	1 290	590
Albania	2 892	20.5	1 400	18.1	130	7 220	70
Andorra	78	13.3	50	20.5	< 5	6 050	< 5
Bosnia and Herzegovina	3 825	18.9	3 700	16.2	150	6 050	170
Former Yugoslav Republic of Macedonia	2 069	28.7	3 000	18.1	110	6 200	90
Iceland	329	5.5	60	11.9	< 5	260	< 1
Kosovo under UNSCR 1244/99	1 805	26.4	3 700	15.8	70	6 130	120
Liechtenstein	37	11.0	20	20.5	< 5	5 800	< 5
Monaco	38	14.4	20	29.7	20	8 020	< 5
Montenegro	622	18.5	640	16.4	20	6 790	30
Norway	5 166	5.9	1 300	12.3	200	1 760	50
San Marino	33	16.2	30	16.2	< 1	7 180	< 5
Serbia	7 114	23.3	13 000	18.4	860	5 280	420
Switzerland	8 238	11.8	4 200	21.4	1 000	6 170	300
EU-28	**506 030**	**13.9**	**391 000**	**18.9**	**76 000**	**4 250**	**16 400**
Total	**538 278**	**14.1**	**422 000**	**18.8**	**79 000**	**4 310**	**17 700**

Notes: [a] The annual mean (in µg/m³) and the SOMO35 (in µg/m³.days), expressed as population-weighted concentration, is obtained according to the methodology described by ETC/ACM (2017a) and not only from monitoring stations; [b] Total and EU-28 premature deaths are rounded to the nearest thousand (except for O_3, nearest hundred). The national totals are rounded to the nearest hundred or ten.

Table 10.2 Years of life lost (YLL) attributable to $PM_{2.5}$, NO_2 and O_3 exposure in 41 European countries and the EU-28, 2015

	$PM_{2.5}$		NO_2		O_3	
Country	**YLL**	**YLL/10^5 inhabitants**	**YLL**	**YLL/10^5 inhabitants**	**YLL**	**YLL/10^5 inhabitants**
Austria	60 200	702	12 200	142	4 000	47
Belgium	77 600	691	16 200	144	2 400	21
Bulgaria	142 000	1 972	6 400	89	3 700	52
Croatia	46 900	1 110	4 500	105	2 500	58
Cyprus	7 400	631	300	26	410	35
Czechia	105 500	1 001	5 100	49	5 000	47
Denmark	30 100	532	860	15	980	17
Estonia	6 300	479	40	3	230	18
Finland	16 000	292	470	9	570	10
France	414 700	624	112 400	169	21 600	32
Germany	638 500	786	134 200	165	31 800	39
Greece	120 700	1 112	23 100	213	6 400	59
Hungary	139 300	1 413	14 300	145	6 000	60
Ireland	12 000	259	310	7	230	5
Italy	593 700	977	200 700	330	32 100	53
Latvia	17 600	886	1400	70	600	30
Lithuania	27 400	938	760	26	940	32
Luxembourg	2 700	480	510	91	110	20
Malta	2 700	629	180	41	180	41
Netherlands	103 800	614	19 900	118	3 300	19
Poland	533 300	1 403	20 400	54	16 600	44
Portugal	56 300	570	9 100	92	3 200	33
Romania	271 600	1 367	14 100	71	6 600	33
Slovakia	59 900	1 105	2 700	51	2 600	47
Slovenia	20 000	970	1 800	88	1 100	53
Spain	290 500	658	92 400	209	19 100	43
Sweden	28 300	290	1 000	10	1 400	14
United Kingdom	324 900	501	99 700	154	6 400	10
Albania	14 500	501	1 300	46	890	31
Andorra	540	692	40	50	40	46
Bosnia and Herzegovina	41 700	1 090	1 700	45	2 000	52
Former Yugoslav Republic of Macedonia	30 400	1 469	1 200	56	1 100	52
Iceland	670	204	30	9	< 5	1
Kosovo	36 300	2 011	650	36	1 300	70
Liechtenstein	210	562	20	64	20	42
Monaco	290	757	170	453	20	61
Montenegro	7 300	1 173	260	42	410	66
Norway	12 900	250	2 000	38	550	11
San Marino	280	854	10	23	20	55
Serbia	127 800	1 796	8 500	119	4 300	60
Switzerland	42 800	520	10 500	128	3 300	40
EU-28	**4 150 000**	**820**	**795 000**	**157**	**180 000**	**36**
Total	**4 466 000**	**830**	**821 000**	**153**	**193 800**	**36**

Note: Total and EU-28 YLL figures are rounded to the nearest thousand or hundred. National data are rounded to the nearest hundred or ten.

10.3 Changes over time of the health impacts of air pollution

A recent study by the ETC/ACM (2018c) assessed the long-term evolution in the exposure of the European population to $PM_{2.5}$ concentrations from 1990 to 2016.

Four different $PM_{2.5}$ concentration datasets, available over several years between 1990 and 2016, were used to estimate the development of population exposure to $PM_{2.5}$ and associated health impacts in the EEA-39 countries, except Turkey. These datasets were:

1. the integrated maps created by the ETC/ACM (ETC-ACM, 2005-2015), which are used as the basis of the EEA's health impact assessments in the annual *Air quality in Europe* report;

2. the Eurodelta-Trends multi-model hindcast (EDT, 1990-2010);

3. the CAMS reanalyses (CAMS, 2014-2016); and

4. the global map of surface $PM_{2.5}$ concentrations developed by the Global Burden of Disease (GBD, 1990-2015).

There were methodological differences between the various concentrations datasets, but all of them were based on a combination of observations and model results.

The concentration datasets were combined with population maps to obtain population-weighted concentrations (similar to the ones shown in Figure 9.1). Finally, from these population-weighted concentration maps, the health impacts were calculated following the same methodology as described in Section 10.1. It should be borne in mind that the same population density data were used for the whole period, but year-to-year changes in country population and mortality were taken into account.

The total premature deaths due to $PM_{2.5}$ exposure across all countries considered in the analysis (EEA-39, except Turkey), ranged from 620 000 to 1 120 000 in 1990 and from 320 000 to 495 000 in 2015, according to the different $PM_{2.5}$ datasets (Figure 10.1). Despite this spread (which also illustrates the challenge in reconstructing exposure to air pollution in the 1990s) between the impacts attributed to $PM_{2.5}$ exposure, the ensemble of all datasets points towards a substantial improvement in health impacts, with a median decrease in mortality of about 60 % across Europe between 1990 and 2015.

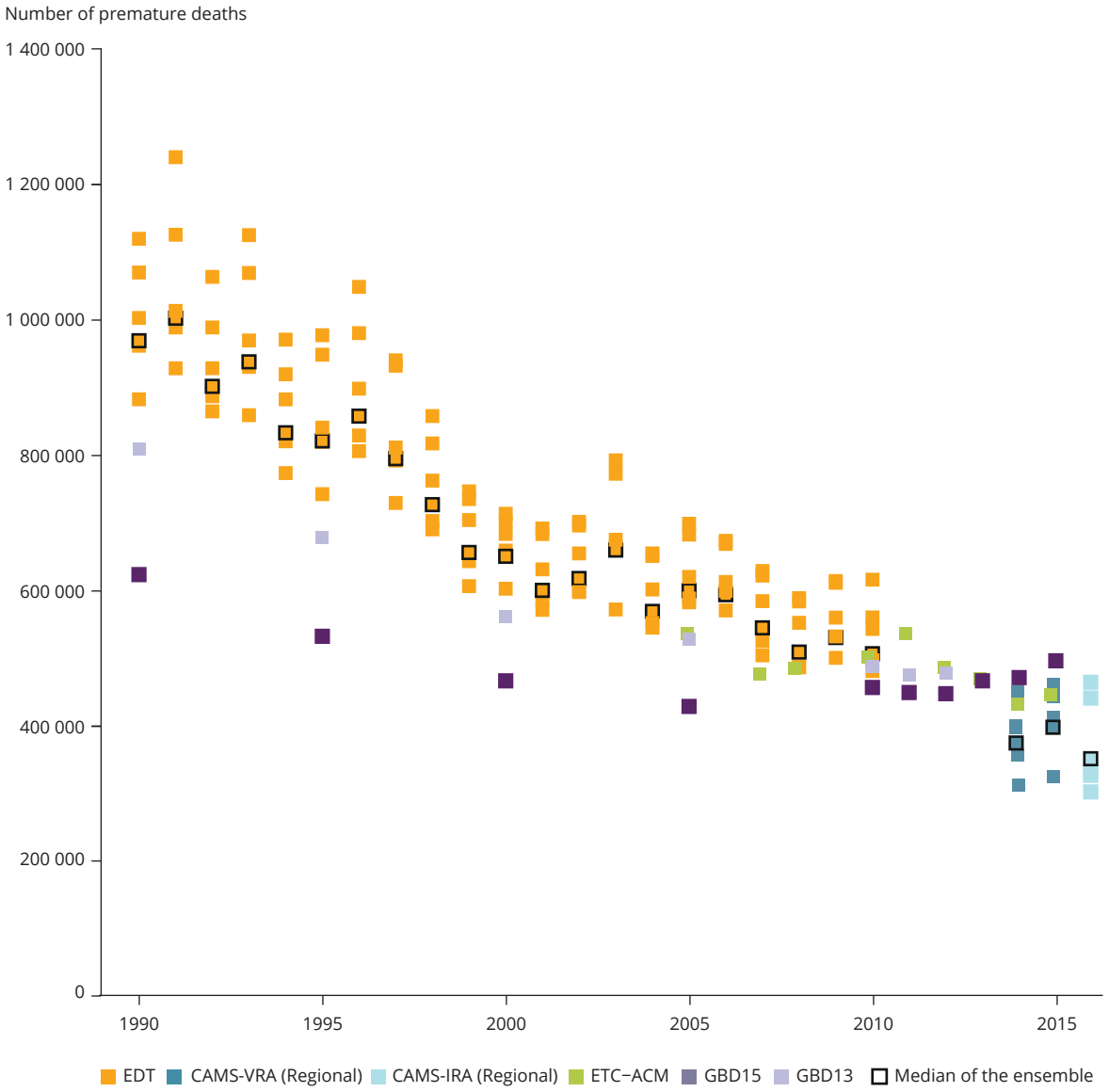
Although the health impact of air pollution remained high across Europe in 2015, the median estimate for all datasets of 445 000 premature deaths per year ([45]) equates to about half a million premature deaths avoided when compared with the situation in 1990 (when the median value was 960 000 deaths per year). Since population has grown in the period 1990-2015, and only total numbers are provided but not death rates, it can be assumed with confidence that the risk associated to air pollution has, at least, halved.

The study also clearly identified a larger reduction in exposure to $PM_{2.5}$ levels, and subsequent health impacts, throughout the 1990s than after the year 2000 and in more recent years, as Figure 10.1 shows.

As explained in previous sections, only total mortality has been considered in these trends and not specific mortality or morbidity indicators. It should be taken into consideration that long-term exposure to even low levels of air pollution is associated with the onset and exacerbation of chronic diseases, such as asthma, ischaemic heart disease, diabetes and neurodegenerative diseases. There are also effects on diseases in new-borns and their life-long impacts.

([45]) This value is different from the 422 000 estimated in Section 10.2 because it was calculated as the median of all the concentrations datasets considered in the study, while in Section 10.2 only the interpolated maps presented in Figure 9.1 were used.

Figure 10.1 **Premature deaths due to exposure to $PM_{2.5}$ (all-cause (natural) mortality) in Europe over the period 1990-2016 for various data sets of $PM_{2.5}$ concentration**



Note: The different datasets are: Eurodelta-Trends (EDT), Copernicus Atmospheric Monitoring Service (CAMS), European Topic Centre on Air Pollution and Climate Change Mitigation (ETC/ACM), and Global Burden of Diseases (GBD, versions 2013 and 2015). For CAMS and EDT, individual participating models are displayed, as well as the ensemble median (black frame).

Source: ETC/ACM, 2018c.

11 Exposure of ecosystems to air pollution

Air pollution leads to environmental degradation, including the degradation of natural ecosystems. Ground-level O_3 can damage crops, forests and other vegetation, impairing their growth and impacting on biodiversity. In many parts of central and southern Europe, EU Natura 2000 grasslands are at risk as a result of exposure to current O_3 levels, which can change plant community composition, and flowering and seed production for some species (Harmens et al., 2016). Changing climatic conditions, and the increase in emissions of CO_2 and other pollutants, such as reactive nitrogen, modify the responses of vegetation to O_3. In addition to affecting plant growth, these modifiers influence the amount of O_3 uptake by leaves, thus altering the magnitude of effects on plant growth, crop yields and ecosystem services (Harmens et al., 2015).

The atmospheric deposition of sulphur and nitrogen compounds has acidifying effects on soils and freshwaters, affecting biodiversity and life on land and in water (Duprè et al., 2010). The deposition of nitrogen compounds can also cause eutrophication, an oversupply of nutrients that may lead to changes in species diversity and invasions by new species. The effects of air pollutants on aquatic ecosystems include the loss of biota sensitive to acidification, as well as increased phytoplankton and harmful algal blooms, which may impact on fisheries, water-based recreational activities and tourism (Greaver et al., 2012). Acidification may also lead to increased mobilisation of toxic metals in water or soils, which increases the risk of uptake in the food chain.

In addition, toxic metals and POPs may have severe impacts on ecosystems. This is mainly because of their environmental toxicity and, in some cases, their tendency to bioaccumulate, a process whereby the toxin cannot be digested and excreted by an animal and, therefore, slowly accumulates in the animal's system, causing chronic health problems. Biomagnification within the food chain may also occur, i.e. increasing concentrations of a pollutant in the tissues of organisms at successively higher levels in the food chain.

11.1 Vegetation exposure to ground-level ozone

High levels of O_3 damage plant cells, impairing plants' reproduction and growth, thereby reducing agricultural crop yields, forest growth and biodiversity ([46]).

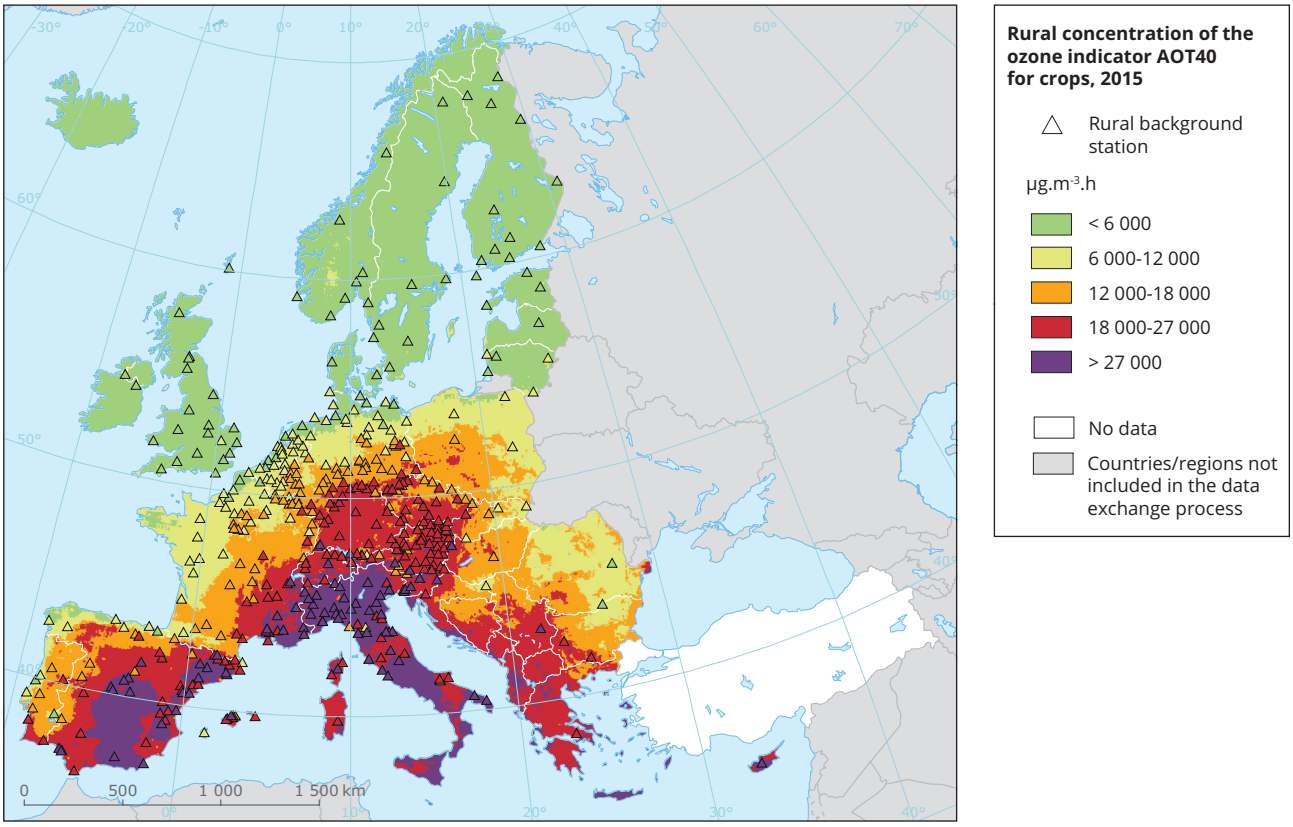
The standards set by the EU to protect vegetation from high O_3 concentrations are shown in Table 1.2. In addition, the UNECE CLRTAP (UNECE, 1979) defines a critical level for the protection of forests.

Since 2000, the AOT40 value of 18 000 µg/m^3.hours has been exceeded in a substantial part of the European agricultural area, as shown in Figure 11.1a (highest parts of the bars), for the EEA-33 member countries (except Turkey; EEA, 2018g). 2015 ([47]) was a year with high O_3 concentrations across Europe (EEA, 2017a). The AOT40 value of 18 000 µg/m^3.hours was exceeded in about 31 % of all agricultural land in all European countries and 30 % of all agricultural land in the EU-28 (i.e. 665 105 km^2 and 602 319 km^2, respectively), mostly in southern Mediterranean regions and parts of central Europe (Map 11.1). O_3 levels vary considerably from year to year, mostly owing to meteorological variations. In 2015, concentrations were higher than in 2014 (EEA, 2017a), when the total area with agricultural crops above the target value was the lowest since 2000. The long-term objective was exceeded in 80 % of the agricultural area across all European countries considered and in 79 % of the agricultural area across the EU-28 in 2015 (ETC/ACM, 2018b).

([46]) Several effects of damage to vegetation by ground-level O_3 were described in the *Air quality in Europe — 2015 report* (EEA, 2015a).

([47]) In the methodology used, the AOT40 is calculated from interpolated maps. To produce these maps, information on the spatial distribution of concentrations from the EMEP model is needed and, at the time of drafting this report, the most up-to-date data from the EMEP model were from 2015 (ETC/ACM, 2018b).

Map 11.1 Rural concentration of the O_3 indicator AOT40 for crops and vegetation, 2015



Source: ETC/ACM, 2018b.

The exceedances since 2004 of the critical level for the protection of forest areas are even more pronounced than in the case of the target value for the protection of vegetation, as shown for the EEA-33 in Figure 11.1b (note that only the lowest parts of the bars correspond to exposures below the critical level). The critical level was exceeded in 60 % of the total forest area in all European countries and in 61 % of the EU-28 forest area (i.e. 925 810 km^2 and 832 512 km^2, respectively) in 2015 (Map 11.2).

11.2 Eutrophication

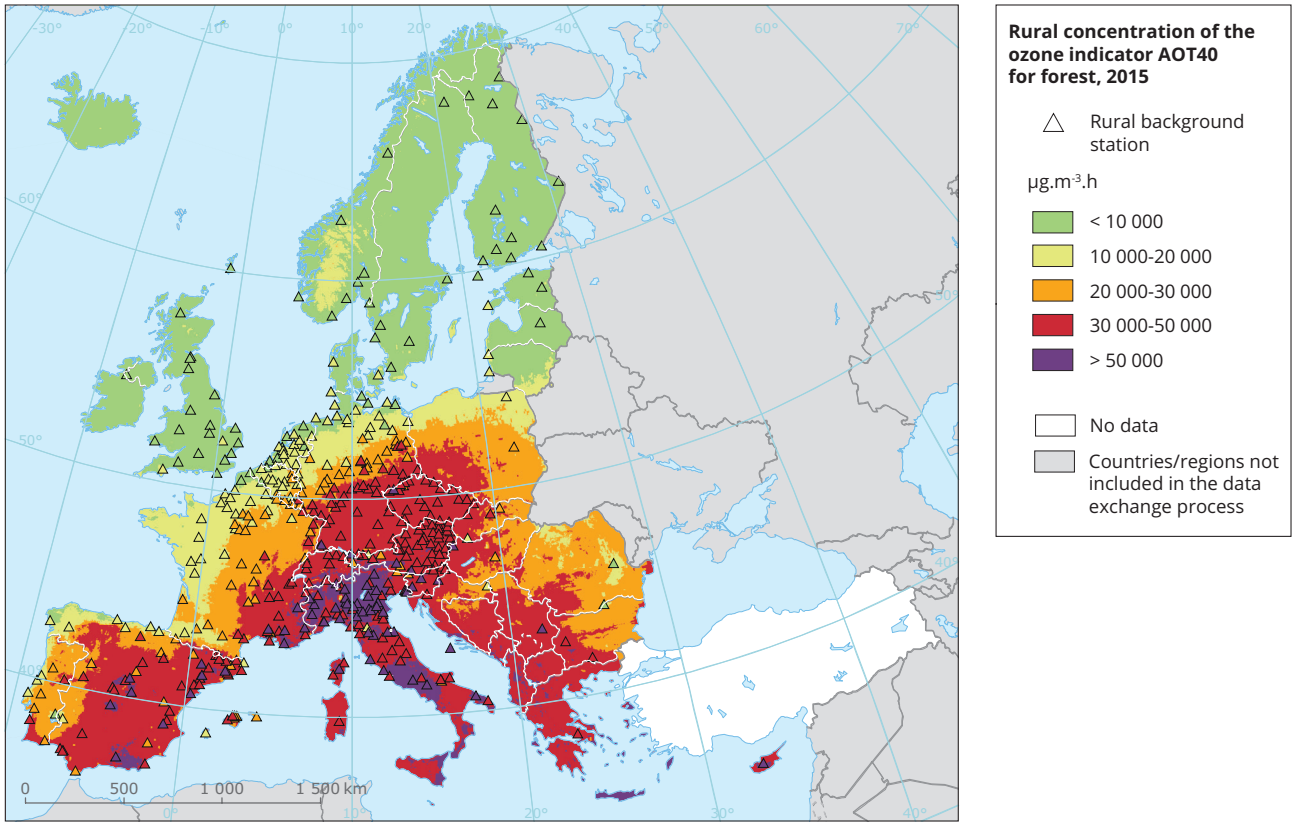
Eutrophication refers to an excess of nutrients in the soil or water, which has several impacts on terrestrial and aquatic ecosystems, including threatening biodiversity (for more information, see EEA, 2016). Air pollution contributes to the excess of nutrient nitrogen, as the nitrogen emitted to the air as NO_x and NH_3 is deposited on soils, vegetation surfaces and waters.

Eutrophication (and acidification) effects due to deposition of air pollution are estimated using the 'critical load' concept. This term describes the ecosystem's ability to absorb eutrophying nitrogen pollutants (or acidifying pollutants, in the case of acidification) deposited from the atmosphere, without the potential to cause negative effects on the natural environment. Exceedances of these spatially determined critical loads present a risk of damage or change to the existing ecosystems. Such exceedances are estimated using ecosystem classification methods and model calculations.

Deposition of inorganic nitrogen on the forest floor has decreased by about 24 % in highly polluted areas and about 16 % on less polluted measurement sites, between 2000 and 2015. Overall, the decrease in nitrate (26 %) has been greater than ammonium (18 %) (ICP Forests, 2018).

EMEP (2017b) estimated that critical loads for eutrophication were exceeded in virtually all European countries and over about 61 % of the European (approximately 72 % of the EU-28) ecosystem area in 2015, confirming that deposition of atmospheric nitrogen remains a threat to ecosystem health in terms of eutrophication. In 2015,

Map 11.2 Rural concentration of the O_3 indicator AOT40 for forests, 2015



Source: ETC/ACM, 2018b.

the highest exceedances occurred in the Po Valley (Italy), the Dutch-German-Danish border areas and north-western Spain. Projections for 2020 and 2030 indicate that ecosystems' exposure to eutrophication will still be widespread (Maas and Grennfelt (eds), 2016; EEA, 2018g). This is in conflict with the EU's long-term objective of not exceeding critical loads of airborne acidifying and eutrophying substances in European ecosystem areas (European Commission, 2005).

Amann (2018) estimated that the measures envisaged for complying with the NEC Directive emission reduction requirements will not be sufficient to achieve the improvements suggested in the 2013 Commission proposal for the NEC Directive (35 % of reduction in the ecosystem area exceeding eutrophication limits). By 2030, the measures are likely to have reduced the proportion of Natura 2000 area where biodiversity is threatened by excess nitrogen deposition, from 78 % (observed in 2005) to 58 %. Additional measures are available, e.g. for controlling agricultural NH_3 emissions, which could further reduce excess nitrogen deposition by 75 %. However, this would still leave 50 % of the Natura 2000 areas at risk.

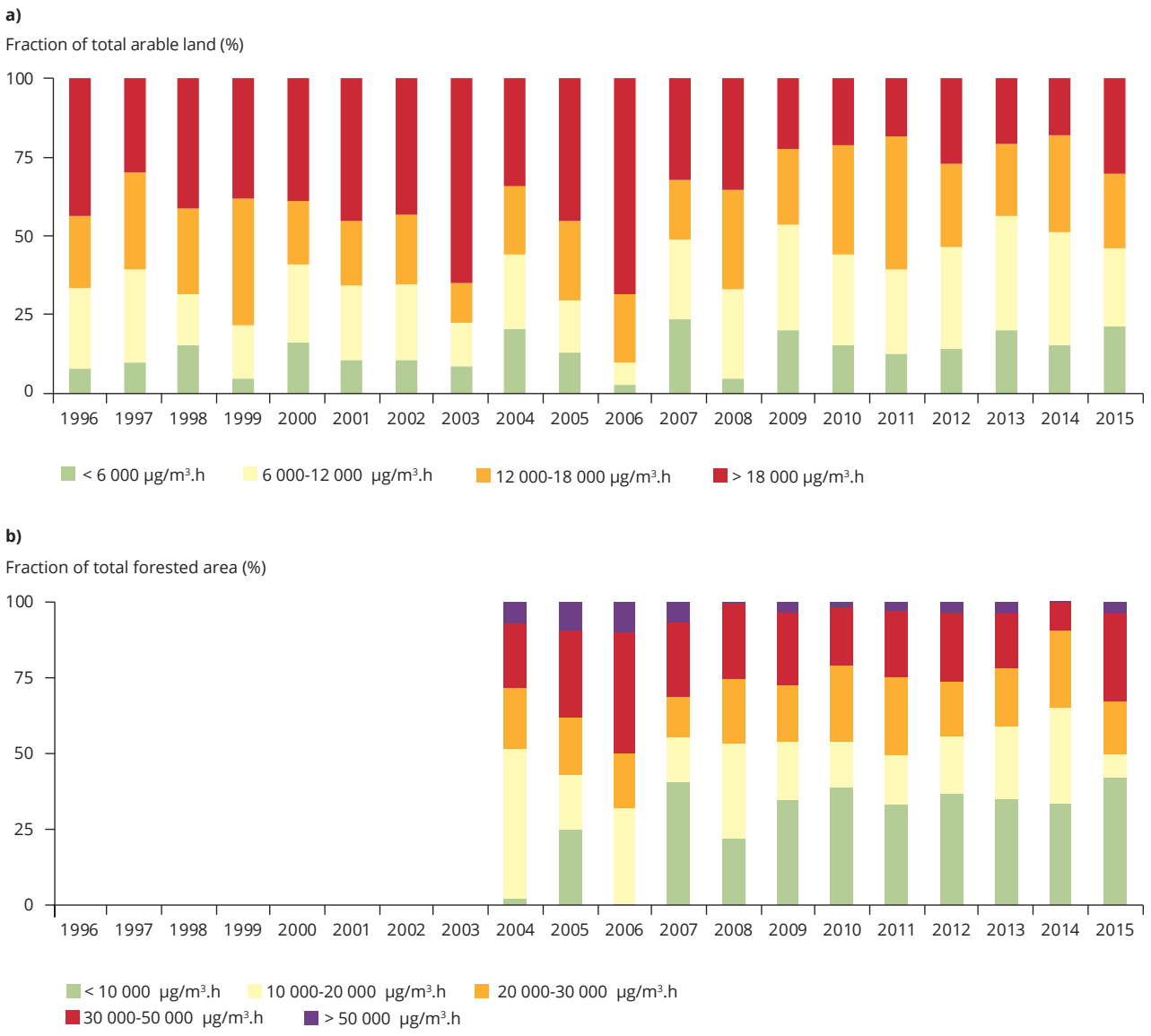
11.3 Acidification

The emission of nitrogen and sulphur into the atmosphere creates nitric acid and sulphuric acid, respectively. The fate of a great amount of these airborne acids is to fall onto the Earth and its waters as acid deposition, reducing the pH level of soil and water, and leading to acidification. Acidification damages plant and animal life, both on land and in water.

After decades of declining sulphur emissions in Europe, acidification is declining or slowing so that some forests and lakes are showing signs of recovery (Maas and Grennfelt (eds), 2016). Owing to the considerable reductions in emissions of SO_x over the past three decades, nitrogen compounds emitted as NO_x have become the principal acidifying components in both terrestrial and aquatic ecosystems, in addition to their role in causing eutrophication. However, emissions of SO_x, which have a higher acidifying potential than NO_x, still contribute to acidification.

Like eutrophication effects, acidification effects are estimated using the concept of 'critical load' (see Section 11.2). EMEP (2017b) estimated that

Figure 11.1 Exposure of (a) agricultural area and (b) forest area to O_3 (AOT40) in the EEA-33 member countries, from 2000 (a) and 2004 (b) to 2015 (µg/m³.hours)



Notes: a) In the Ambient Air Quality Directive (EU, 2008), the target value for protection of vegetation is set at 18 000 µg/m³.hours, averaged over 5 years, whereas the long-term objective is set at 6 000 µg/m³.hours. Only yearly values of the AOT40 are considered in the graph, without any averaging over years. Owing to a lack of detailed land cover data and/or rural O_3 data, Iceland and Norway were not included until 2007; Switzerland was not included until 2008; and Turkey is not included throughout the entire period.

b) The UNECE CLRTAP (UNECE, 1979) has set a critical level for the protection of forests at 10 000 µg/m³.hours. In 2005, Bulgaria, Greece and Romania were added to the calculations, in 2007, Iceland and Norway, and, in 2008, Switzerland. Since 2008, only Turkey has not been included, as a result of a lack of detailed land cover data and/or rural O_3 data. Calculations of forest exposure are not available for the years prior to 2004.

Source: EEA, 2018g.

exceedances of the critical loads for acidification occurred over about 5 % of the European ecosystem area and 6 % of the EU-28 ecosystem area in 2015. Hotspots of exceedances occurred in the Netherlands and its areas that border Germany and Belgium, as well as in southern Germany. However, most of Europe did not exceed the critical loads for acidification in 2015. Looking forward, 4 % of the EU-28 ecosystem area (3 % in EEA member countries) is projected to exceed acidification critical loads in 2020 if current legislation is fully implemented (EEA, 2018g).

Amann (2018) estimated that the further reduction in SO_2 emissions in order to comply with the NEC Directive requirements will resolve most of the threat of acidification of forest soils, and full implementation

of additional reduction potentials would allow meeting the critical loads for acidification at 99.8 % of all European forest areas.

11.4 Vegetation exposure to nitrogen oxides and sulphur dioxide

Critical levels for NO_x and SO_2 for the protection of vegetation are set by the Ambient Air Quality Directive (EU, 2008), as shown in Table 1.2.

The NO_x annual critical level for the protection of vegetation (30 µg/m^3) was exceeded in 2016 at nine rural background stations in Italy (three), the Netherlands (three), Germany (one) and Switzerland (two).

ETC/ACM (2018b) estimated that in most areas of Europe the annual NO_x means are below 20 µg/m^3. However, in the Po Valley and a few rural areas close to major cities, elevated NO_x concentrations above the critical level were estimated for 2015 (map 5.2 in ETC/ACM, 2018b).

In 2016, there were no exceedances of the SO_2 annual or winter critical levels in any of the reported rural background stations.

11.5 Environmental impacts of toxic metals

Toxic metal pollutants can cause harmful effects in plants and animals, in addition to humans. Although the atmospheric concentrations of As, Cd, Pb, Hg and Ni may be low, they still contribute to the deposition and build-up of toxic metals in soils, sediments and organisms. These toxic metals do not break down in the environment and some bioaccumulate and biomagnify. This means that plants and animals can be poisoned over a long period through long-term exposure to even small amounts of toxic metals. If a toxic metal has bioaccumulated in a particular place in the food chain — for example in a type of fish — then consumption of that fish by humans may present a serious risk to their health.

The EMEP (2017a) model estimated the deposition of Pb, Cd and Hg in ecosystems. Hotspots of high Cd deposition on croplands are located in the Benelux countries, southern Poland, northern Italy, the central part of the European territory of Russia, and territories adjacent to the Black Sea, while relatively low deposition fluxes were modelled over Spain, France and Scandinavia.

Based on updated European Pollutant Release and Transfer Register (E-PRTR) emission data for toxic metals reported in 2016, and using the aggregated eco-toxicity approach (USEtox model), the EEA (2018d) outlines the combined environmental pressures on Europe's environment caused by releases of eight metals (As, Cd, Pb, Hg, Ni, chromium, copper and zinc). Of the 978 facilities releasing heavy metals into the air in 2016, only 18 were responsible for more than half of the associated environmental pressure. The environmental pressure exerted by emissions of toxic metals into the air was 39 % lower in 2016 than in 2010 (EEA, 2018d).

Abbreviations, units and symbols

µg/m³	Microgram(s) per cubic metre
AEI	Average exposure indicator for $PM_{2.5}$ concentrations
AOT40	Accumulated exposure over a threshold of 40 ppb. This represents the sum of the differences between hourly concentrations > 80 µg/m³ (40 ppb) and 80 µg/m³ accumulated over all hourly values measured between 08:00 and 20:00 Central European Time
AQG	Air Quality Guideline
As	Arsenic
BaP	Benzo[*a*]pyrene
BC	Black carbon
CAMS	Copernicus Atmosphere Monitoring Service
CAPE	Clean Air Programme for Europe
C_6H_6	Benzene
Cd	Cadmium
CH_4	Methane
CL	Critical level
CLRTAP	Convention on Long-range Transboundary Air Pollution
CO	Carbon monoxide
CO_2	Carbon dioxide
ECO	Exposure concentration obligation
EDT	Eurodelta-Trends
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Programme
E-PRTR	European Pollutant Release and Transfer Register
ESD	Effort Sharing Decision
ESR	Effort Sharing Regulation
ETC/ACM	European Topic Centre for Air Pollution and Climate Change Mitigation
ETS	Emissions Trading System

EU	European Union
EUR	Euros
GBD	Global Burden of Disease
GDP	Gross domestic product
GVA	Gross value added
Hg	Mercury
HRAPIE	Health Risks of Air Pollution in Europe
K^+	Potassium
LAT	Lower assessment threshold
mg/m^3	Milligram(s) per cubic metre
Mg^{2+}	Magnesium
NEC	National Emission Ceilings (Directive)
NERT	National exposure reduction target
ng/m^3	Nanogram(s) per cubic metre
NH_3	Ammonia
NH_4^+	Ammonium
NH_4NO_3	Ammonium nitrate
$(NH_4)_2SO_4$	Ammonium sulphate
Ni	Nickel
NMVOC	Non-methane volatile organic compound
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NO_3^-	Nitrate
NO_x	Nitrogen oxides
O_3	Ozone
OECD	Organisation for Economic Co-operation and Development
PAH	Polycyclic aromatic hydrocarbon
Pb	Lead
PM	Particulate matter
$PM_{2.5}$	Particulate matter with a diameter of 2.5 µm or less
PM_{10}	Particulate matter with a diameter of 10 µm or less
POPs	Persistent organic pollutants

pkm	Passenger-kilometre
ppb	Parts per billion
RL	Reference level
SDG	Sustainable Development Goals
SO_2	Sulphur dioxide
SO_4^{-2}	Sulphate
SOMO35	Accumulated O_3 concentration (8-hour daily maximum) in excess of 35 ppb
SO_x	Sulphur oxides
tkm	Tonne-kilometre
TOE	Tonne of oil equivalent
UN	United Nations
UNEA	United Nations Environment Assembly
UNECE	United Nations Economic Commission for Europe
UNSCR	United Nations Security Council Resolution
USD	United States dollars
VOC	Volatile organic compound
WHO	World Health Organization
WMO	World Meteorological Organization
YLL	Years of life lost

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Annex 1 Sensitivity analysis of the health impact assessments

Apart from the impacts estimated for the full range of observed $PM_{2.5}$ concentrations, meaning all concentrations from 0 µg/m³ upwards, the impacts from a $PM_{2.5}$ concentration of 2.5 µg/m³ are also shown here. It corresponds to the lowest concentration found in populated areas (ETC/ACM, 2017a) and represents an estimate of the European background concentration.

Equally, for NO_2, in addition to the impacts calculated for a concentration above 20 µg/m³, the impacts from an NO_2 concentration of 10 µg/m³ are shown here. The value 10 µg/m_3 corresponds to the lowest observed value in a study (Raaschou-Nielsen et al., 2012) that showed a significant correlation between NO_2 concentrations and health outcomes at this concentration level.

The results are presented in Table A1.1. Both for the EU-28 ('EU-28') as well as for the 41 countries considered ('Total'), the number of premature deaths and YLL attributable to $PM_{2.5}$ from a concentration of 2.5 µg/m³ is estimated to be about 18 % lower than in the case of 0 µg/m³.

In the case of NO_2, the estimated health impacts from a concentration of 10 µg/m³ are around three times higher than those from a concentration of 20 µg/m³. However, at national level the increase might be (much) larger than a factor of three, assuming that a lower concentration does not only lead to an increase in the estimated impacts but also to changes in the spatial distribution. Figure 9.1 shows that in large parts of Europe concentrations are below 20 µg/m³. In 36 (out of 41) countries more than 50% of the population is exposed to concentrations below 20 µg/m³; for this part of the population, health impacts are not quantified when starting from a concentration of 20 µg/m³.

Table A1.1. Estimated number of premature deaths and years of life lost attributable to $PM_{2.5}$ (from a concentration of 2.5 µg/m³) and NO_2 (from a concentration of 10 µg/m³), reference year 2015

	$PM_{2.5}$	NO_2
Concentration (µg/m³)	**2.5**	**10**
Total		
Premature deaths	352 000	241 000
Years of life lost	3 718 000	2 515 000
EU-28		
Premature deaths	325 000	228 000
Years of life lost	3 444 000	2 385 000

Note: Totals for 41 European countries ('Total') and EU-28 Member States ('EU-28').

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