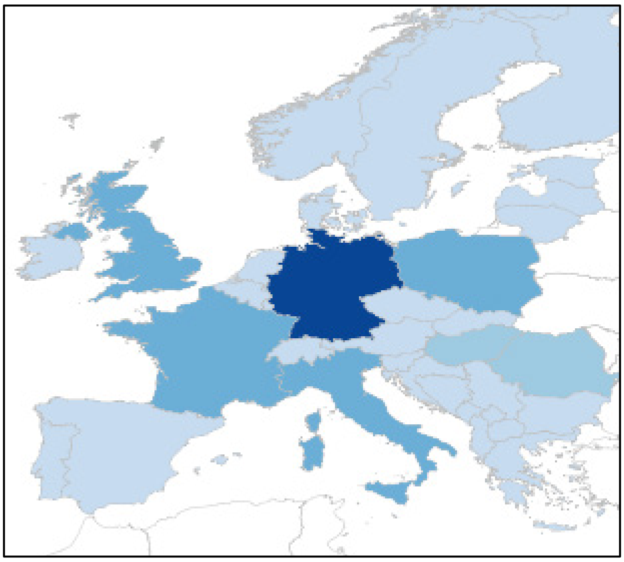
Long-term air quality trends in Europe

Fine Particulate Matter ($PM_{2.5}$) Health Impacts



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European Topic Centre on Air Pollution and Climate Change Mitigation

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Front page picture:
Rate of decline in mortality between 1990 and 2010, Figure 9 of the present report

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Executive summary

The population exposure to ambient fine particulate matter ($PM_{2.5}$) is investigated to document how the differences amongst various data sets of $PM_{2.5}$ concentrations translate into long-term health impact assessment of air pollution over Europe. In addition to ETC/ACM maps of $PM_{2.5}$, the Copernicus Atmospheric Monitoring Service analyses, Global Burden of Disease and World Health Organization maps as well as the Eurodelta-Trends reanalysis are also considered. The time-period covered by the data sets ranges from 1990 to 2016.

A substantial reduction of the adverse health impacts of air pollution is found. The median estimate of mortality for 1990 was about 960 000 death per year; in 2015 the burden remained high, with 445 000 death per year. Still, that is almost 500 000 avoided premature deaths per year.

Three consistent long term data sets are available for the two decades covering 1990-2010: Eurodelta-Trends and the two version of the Global Burden of Diseases (GBD13 and GBD15). While all source of data indicate that the decline was faster in the 1990s compared to the 2000s, the spread remains very high. In 1990, the range of $PM_{2.5}$ exposure (expressed as population-weighted concentration) extends from 20 $\mu g/m^3$ to 37 $\mu g/m^3$ on average over Europe depending on the estimates, that is almost a factor two (which is also the order of uncertainty of the relative risk functions used to assess mortality impacts). The relative change between 1990 and 2010 ranges from -30% in the GBD15 estimate to -52% in Eurodelta-Trends. While these difference can be explained by methodological differences, it would be helpful to seek independent validation strategies in order to reduce uncertainties.

1 Scope and structure

Exposure to ambient fine particulate matter ($PM_{2.5}$) air pollution leads to substantial health impacts with 428,000 deaths reported for Europe[1] in 2014 according to the *Air Quality in Europe - 2017 Report* of the European Environment Agency (EEA, 2017). Such estimate presents an uncertainty of ± 35 %, due to the uncertainties in the health impact assessment methodology (underlying mortality and population data, and concentration-response functions). Another cause of uncertainty is the exposure to ambient PM. The present report addresses the uncertainty on the latter, showing estimations of the health impacts derived from $PM_{2.5}$ concentration maps available from various sources for the period 1990 to 2016.

The PM exposure data included in this assessment rely on data from in situ air quality monitoring stations, output of chemistry transport models, satellite observations or combinations of them. The selected data sets are:

- The European Topic Centre on Air pollution and Climate change Mitigation (ETC/ACM) exposure maps (Horálek et al., 2016)
- The Copernicus Atmospheric Monitoring Service (CAMS) analyses[2]
- The EuroDelta-Trends (EDT) reanalysis produced in the framework of the EMEP Task Force on Measurement and Modelling (Colette et al., 2017a)
- The Global Burden of Disease (GBD, for both 2013 and 2015 versions) and the World Health Organization (WHO)[3]

The specific characteristics of the data sets are presented in Section 2, and a comparison for the whole of Europe (defined here as EEA39 countries except Turkey[4]) and at country level is shown in Section 3. The methodology used to derive health impact estimates is described in Section 4.1 and the results are shown in Section 4.2, focusing on the differences related to the various sets of $PM_{2.5}$ data.

[1] For 41 European countries as shown in Table 10.1 in (EEA, 2017).
[2] http://policy.atmosphere.copernicus.eu/Reports.html
[3] http://who.int/phe/health_topics/outdoorair/databases/modelled-estimates/en/
[4] Albania, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Kosovo under United Nations Security Council Resolution 1244/99, Latvia, Lithuania, Liechtenstein, Luxembourg, the former Yugoslav Republic of Macedonia, Malta, Montenegro, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Serbia, Sweden, Switzerland, and United Kingdom. Turkey is not included due to a lack of monitoring data for $PM_{2.5}$.

2 Air pollution and population data

2.1 Particulate matter concentrations

The exposure of European population to air pollution from particulate matter was assessed based on various data sets of $PM_{2.5}$ concentration maps covering the whole of Europe (here defined as EEA 39 except Turkey, see footnote on previous page), at a spatial resolution of 25 km or higher, from 1990 to 2016. The main features of the data sets are summarized in Table 1 and presented in the following subsections.

All the available $PM_{2.5}$ concentration data sets rely on in-situ observed $PM_{2.5}$ concentrations from the Air Quality (AQ) e-reporting database[5]. They differ in the strategy used to combine the observations and the results of Chemistry-Transport Models (CTMs) (data fusion or data assimilation), and some of them also make use of satellite or land-use data. The other differences of data sets are: the time period covered, the spatial resolution and the temporal frequency of available concentration data. A last important difference regards the update frequency. For some data sets, the historical data were reconstructed recently making the best use of latest knowledge and offering a consistent temporal approach (therefore referred to as reanalyses). Otherwise, historical data produced sometimes up to 10 years ago were used and, in this case, the methodology may vary from year to year (therefore referred to as analyses).

[5] https://www.eea.europa.eu/data-and-maps/data/aqereporting-2, last accessed 17 Nov 2017. Previously, AirBase.

Table 1: Ambient $PM_{2.5}$ concentration data sets available over Europe for the period 1990-2016.

Data sets	Years	Horizontal Resolution	Methodology
ETC/ACM	2005, 2007, 2008, 2010-2015	1 km	AQ e-reporting (or Airbase) kriged with EMEP MSC-W model, altitude and meteo information, separate urban and rural maps merged using population density
Eurodelta-Trends (EDT)	1990-2010	25 km	AQ e-reporting kriged with an ensemble reanalysis of CTMs
CAMS	2014-2016	10 km	AQ e-reporting kriged or assimilated in an ensemble of CTMs
GBD13	1990, 1995, 2000, 2005, 2010-2013	10 km	Satellite data corrected with in situ observations and modelled concentrations
GBD15	1990, 1995, 2000, 2005, 2010-2015	10 km	Satellite data corrected with in situ observations and modelled concentrations (revised methodology compared to GBD13)
WHO	2014	10 km	Same methodology as GBD15

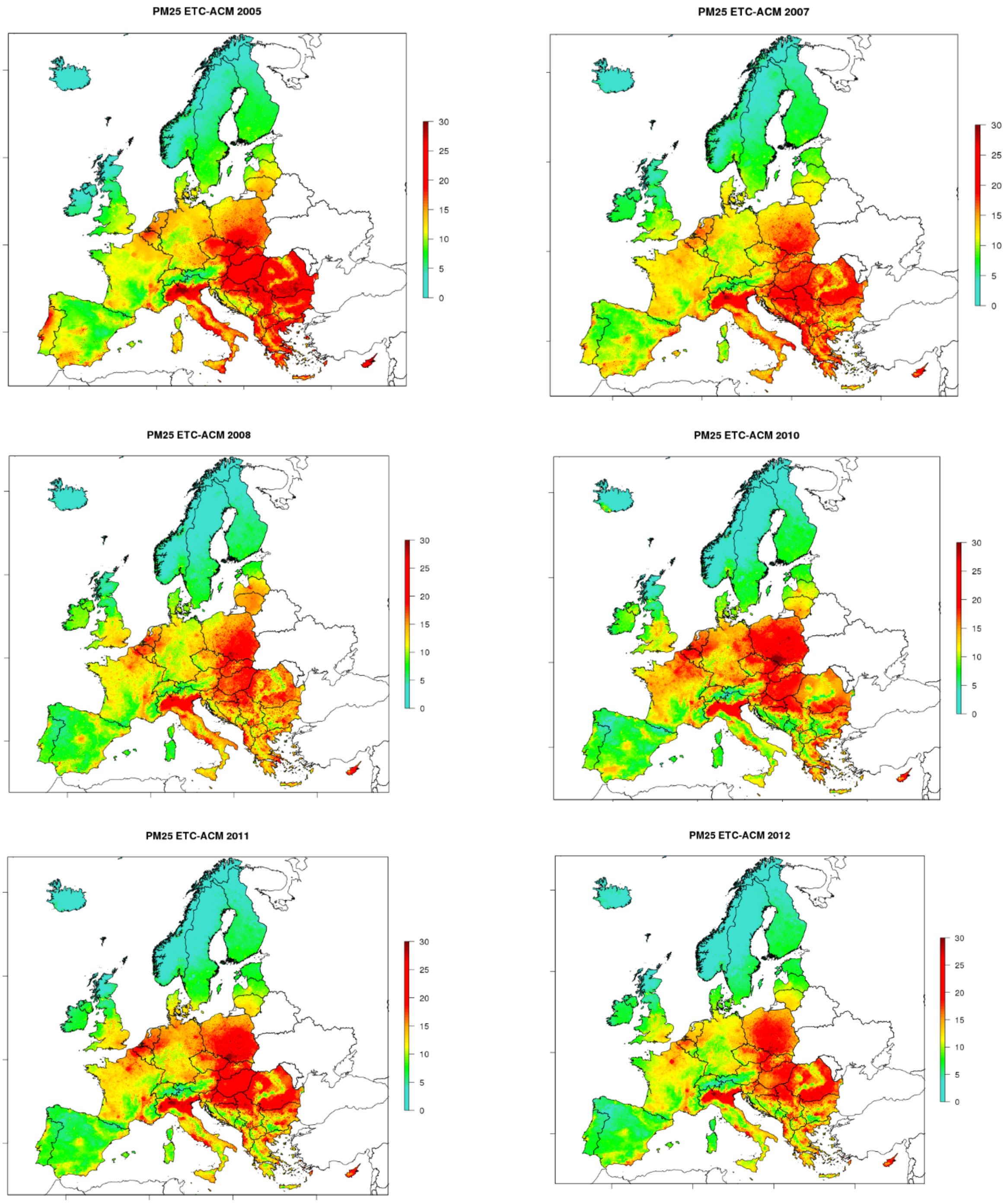
2.1.1 ETC/ACM

The maps of $PM_{2.5}$ concentrations produced by the European Topic Centre on Air Pollution and Climate Change Mitigation (ETC/ACM) are estimated by kriging of in-situ surface measurements with the concentrations simulated by an underlying CTM. In-situ observations are those of the Air Quality e-reporting database for $PM_{2.5}$ concentrations. The dataset is supplemented with $PM_{2.5}$ pseudo-data estimated with a multi-parameter linear model from observed PM_{10} concentrations which are better monitored over Europe (Denby et al., 2011).

In-situ measured $PM_{2.5}$ concentrations, and pseudo-data derived from PM_{10}, are kriged using the EMEP MSC-W model at 50 km resolution (Simpson et al., 2012) as an external drift, and also CORINE land-cover and topographic data. Different types of stations (either urban and suburban or rural) are treated independently in the kriging method, before being merged on a 1 km resolution European grid, taking into account the variability between either urban and suburban or rural areas.

The years 2005, 2007, 2008, 2010, 2011, 2012, 2013, 2014 and 2015 are included in the present assessment (2006 and 2009 are not included because years prior to 2010 were not produced on a regular basis at the time). Note that there was a change in the ETC/ACM kriging methodology related to the population data used from 2013 onwards (Geostat 2011 instead of JRC, see section 2.2). Therefore, for consistency purposes, the exposure data for the period 2005-2011 were re-scaled from the original ETC/ACM maps onto the Geostat population estimates (see Section 2.2 for further information on the various population sources).

Figure 1 shows the maps of $PM_{2.5}$ concentrations developed by the ETC/ACM. They illustrate well the high spatial resolution of ETC/ACM maps compared to the other available products presented in the following sections.



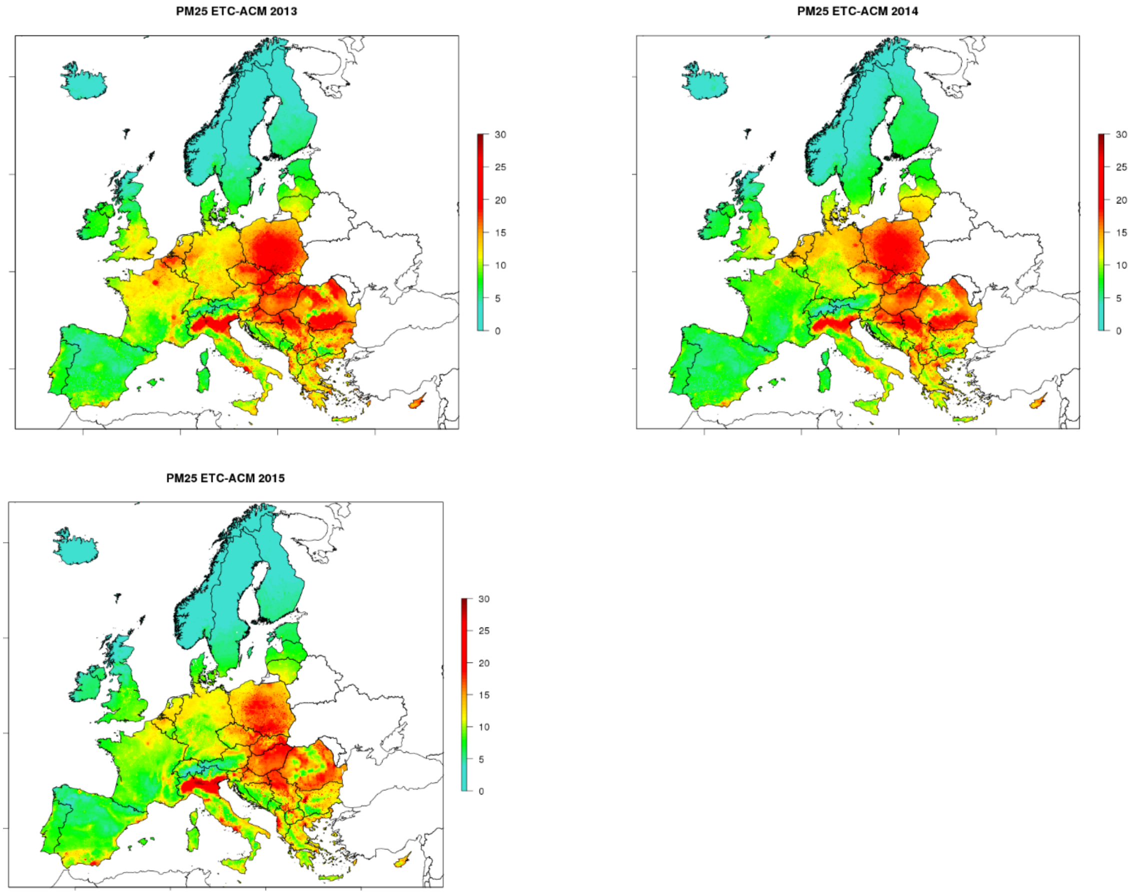


Figure 1: **Maps of $PM_{2.5}$ ($\mu g/m^3$) concentrations for the period 2005-2015 (excluding the years 2006 and 2009) produced by the ETC/ACM by means of data fusion between observations, the EMEP MSC-W chemistry-transport model, altitude, meteorology and land-use data.**

2.1.2 Eurodelta-Trends

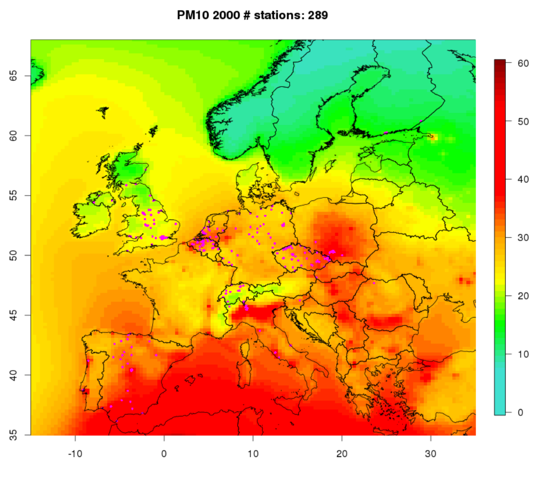
A multi-model trend ensemble was recently compiled by the EMEP Task Force on Measurement and Modelling (TFMM) under the Convention on Long Range Transboundary Air Pollution (CLRTAP) in order to explore the skills of regional CTMs in capturing air pollution trends. A complete description of the modelling exercise is available in (Colette et al., 2017a). A report including a validation of the Eurodelta-Trend (EDT) ensemble was also published in 2017 by ETC/ACM (Colette et al., 2017b).

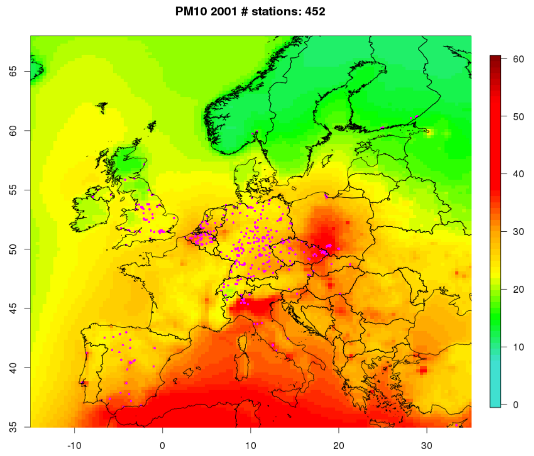
The exercise covered the period 1990-2010. The year 1990 was chosen because it is used as reference for the initial Gothenburg Protocol of 1999[6], while the last year was chosen based on the availability of underlying forcing data (emission, boundary conditions and meteorology) when the modelling exercise was initiated. The modelling domain covers the European region (17°W to 39.8°E and 32°N to 70°N) and the model resolution is 0.25° x 0.4° of latitude x longitude, which in Europe is approximately 25 km.

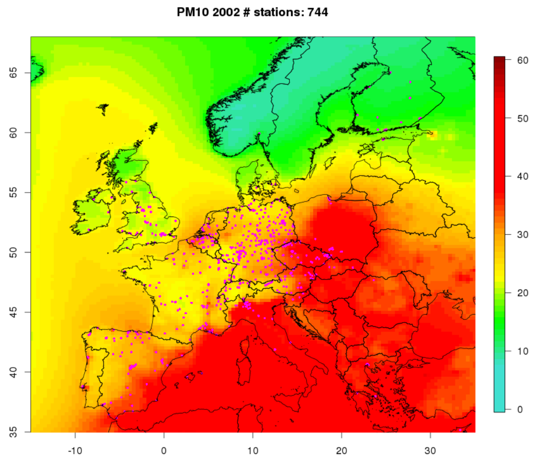
[6] Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, http://www.unece.org/env/lrtap/multi_h1.html

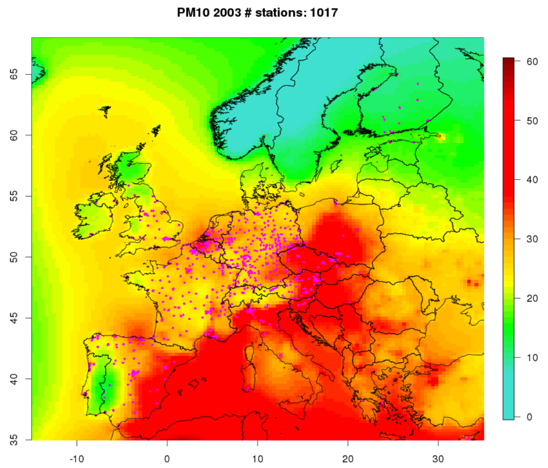
All models use identical trends in anthropogenic emissions. IIASA computed the anthropogenic emissions with the GAINS model, as part of the ECLIPSE project, and provided them to the EDT study. More details on these emissions can be found in (Amann et al., 2012) and (Klimont et al., 2017). These emissions were gap-filled with EMEP country totals for countries and areas not included in the GAINS model. However an error was identified in this gap filling for primary PM species for the years 1991 to 1999 at a stage when it was not possible to re-run all the models. Additional simulations performed with one model (CHIMERE) demonstrate that the impact of this issue on the 1990-2010 trend estimate is less than 1% on average over EEA38 countries, which is much lower than other sources of uncertainties. The time series discussed below in Figure 3 also show that the 1991-1999 period does not display any suspicious feature. A single source of chemical boundary conditions is also used. It consists of a simplified version of those used in the standard EMEP MSC-W model (Simpson et al., 2012), and is based on in situ observation trends, in particular at the Mace-Head observatory, in Ireland. A common source of meteorological forcing is provided based on a dynamic downscaling of ECMWF reanalyses with the WRF model (Stegehuis et al., 2015). The other processes are model dependant, including on-line computation of biogenic emissions.

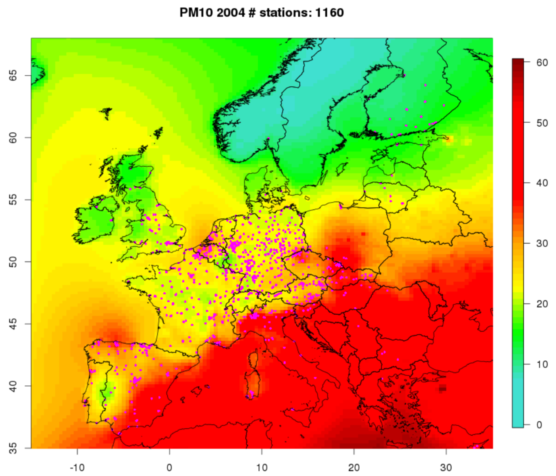
The raw model outputs are corrected by means of data fusion using daily PM_{10} and $PM_{2.5}$ observations at urban, suburban and rural sites from the Air Quality e-reporting database, and the ensemble of EDT models constitutes the external drift in the kriging. A median of CHIMERE (Menut et al., 2013;Mailler et al., 2017), EMEP MSC-W (Simpson et al., 2012) and LOTOS-EUROS (Sauter et al., 2012;Schaap et al., 2008;Manders et al., 2017) is used for the external drift since the other models were not available at the time the kriging was performed. Because of the scarcity of PM observations in the earlier years, the fusion of EDT models with observations is only performed for the years 2000-2010 and 2007-2010 for PM_{10} and $PM_{2.5}$, respectively. Figure 2 depicts annual mean maps of PM_{10} and $PM_{2.5}$ concentrations in those analyses. As indicated in the title of the individual panels, the number of monitoring stations varies substantially in time, from 289 to 1900 for PM_{10} and from 159 to 467 for $PM_{2.5}$. Such changes in the network can have a strong impact on the data fusion results, the sharp increase of $PM_{2.5}$ in southern Poland over 2007-2010 could be an illustration of this artifact.




PM10 2001 # stations: 452
65
60
55
50
45
40
35
-10
0
10
20
30
60
50
40
30
20
10
0


PM10 2002 # stations: 744
65
60
55
50
45
40
35
-10
0
10
20
30
60
50
40
30
20
10
0


PM10 2003 # stations: 1017
65
60
55
50
45
40
35
-10
0
10
20
30
60
50
40
30
20
10
0


PM10 2004 # stations: 1160
-10
0
10
20
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35
40
45
50
55
60
65
0
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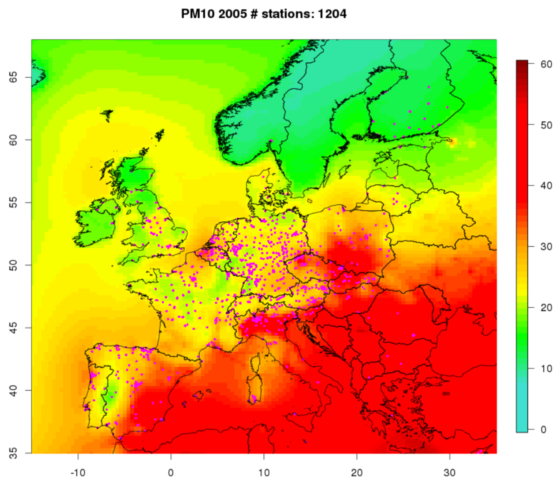
40
50
60


PM10 2005 # stations: 1204
-10
0
10
20
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35
40
45
50
55
60
65
0
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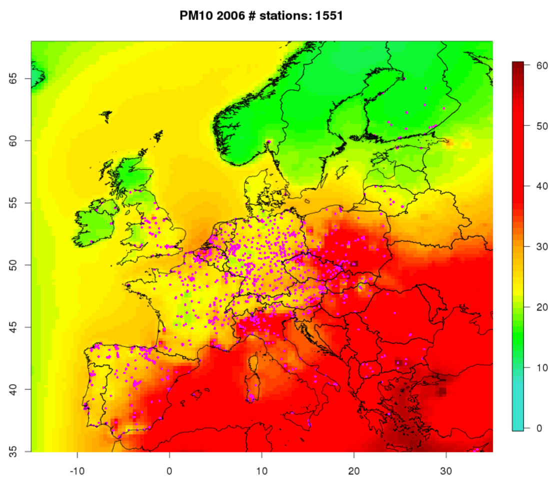
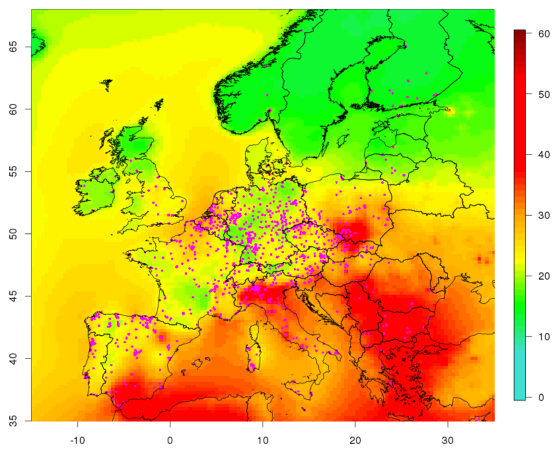
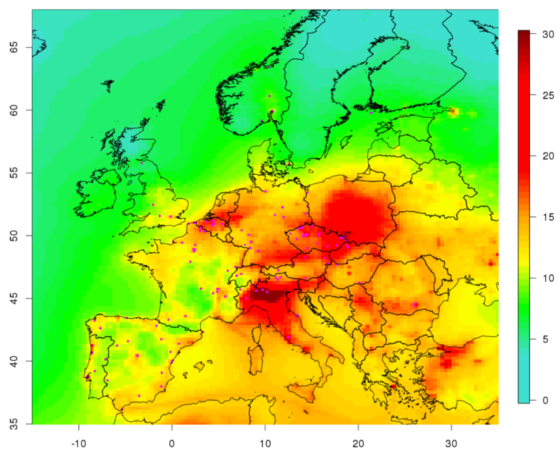
30
40
50
60


PM10 2006 # stations: 1551
-10
0
10
20
30
35
40
45
50
55
60
65
0
10
20
30
40
50
60

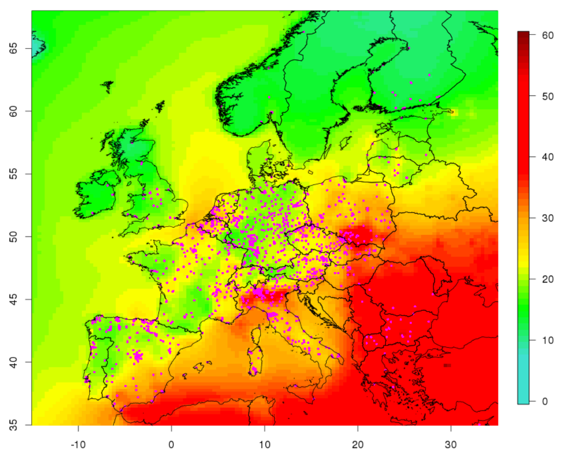
PM10 2007 # stations: 1585



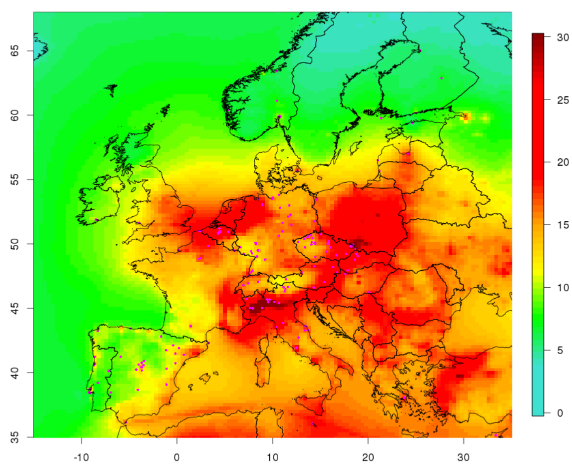
PM25 2007 # stations: 159



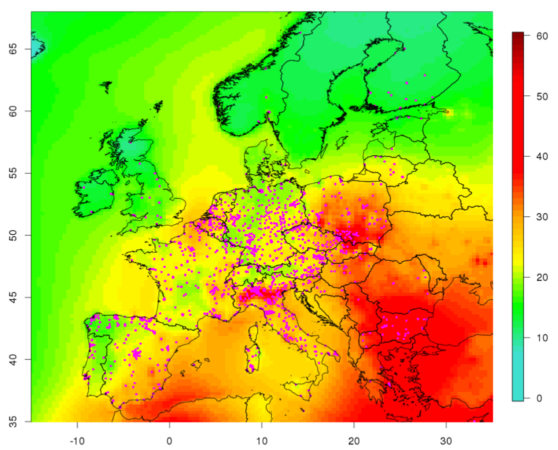
PM10 2008 # stations: 1734



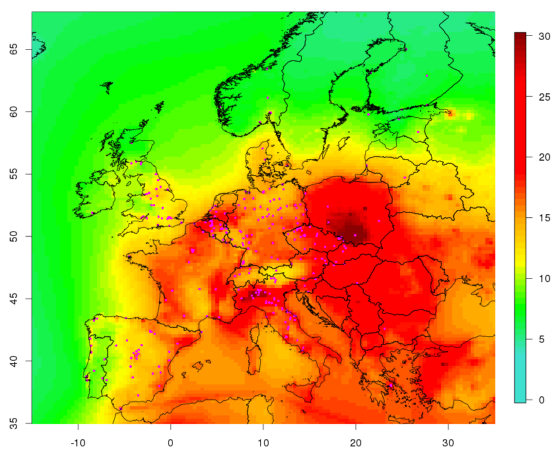
PM25 2008 # stations: 181



PM10 2009 # stations: 1876



PM25 2009 # stations: 336



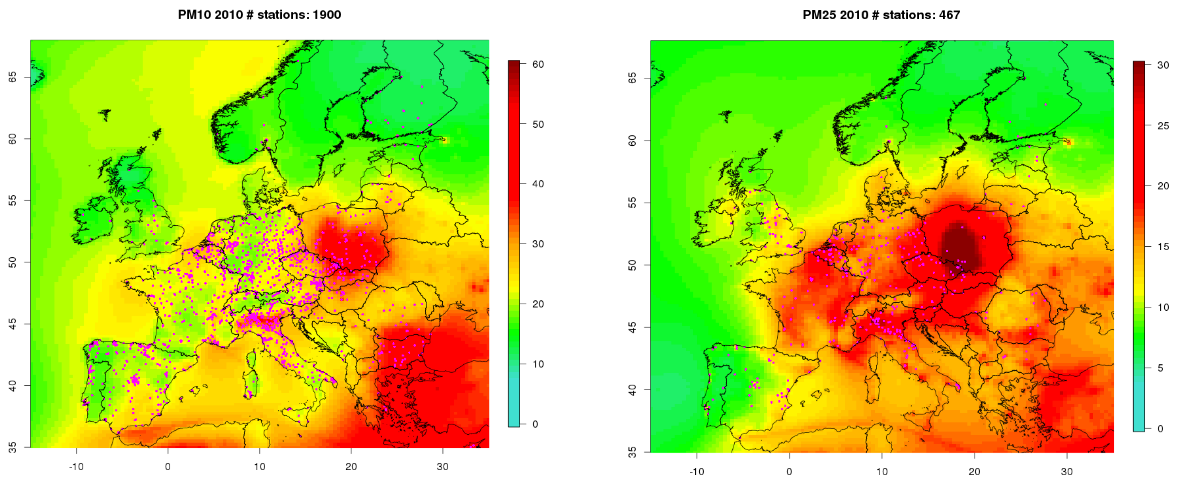


Figure 2: **Maps of PM_{10} (2000-2010, left) and $PM_{2.5}$ (2007-2010, right) concentrations in the Eurodelta-Trends multi-model ensemble accounting for in situ observations (monitoring stations indicated with pink dots) with data fusion method. Note the different colour scales for PM_{10} and $PM_{2.5}$. # stations indicate the number of monitors used in the kriging for each year.**

The $PM_{2.5}$ concentration is the main variable of interest in terms of health impacts because, currently, mortality response functions are retrieved only for the total bulk of $PM_{2.5}$ concentration. Therefore, it is desirable to implement a specific reconstruction methodology for this variable in order to make use of the whole time-period available in the full EDT database (i.e. 1990-2010). To summarize, the following fields are available in the Eurodelta-Trends database:

a) Ensemble median of raw modelled $PM_{2.5}$ fields, which is available for 1990-2010.
b) Ensemble median of raw modelled PM_{10} fields, which is available for 1990-2010.
c) Analysis of observed $PM_{2.5}$ concentrations, which is kriged with the multi-model ensemble median and available for 2007-2010.
d) Analysis of observed PM_{10} concentrations, which is kriged with multi-model ensemble median and available for 2000-2010

For the complete 1990-2010 period, two strategies can be considered to develop a proxy $PM_{2.5}$ using the four datasets (a, b, c, and d, listed above) :

1. Proxy $PM_{2.5}$ based on $PM_{2.5}$: Scaling (a) on the basis of the ratio between raw $PM_{2.5}$ (a) and corrected $PM_{2.5}$ (c)
2. Proxy $PM_{2.5}$ based on PM_{10}: Scaling (b) on the basis of (i) the ratio between modelled PM_{10} and $PM_{2.5}$ (a and b), and (ii) the ratio between raw (b) and corrected PM_{10} (d).

Both approaches have pros and cons. The option based on $PM_{2.5}$ (1) requires fewer approximations, in particular regarding the stationarity of the $PM_{10}/PM_{2.5}$ ratio. However, it relies on less data since $PM_{2.5}$ monitoring is not as developed as PM_{10} monitoring. Only the years 2008-2010 are included in the bias correction because the dataset for 2007 is too limited. The option based on PM_{10} (2) is better constrained with PM_{10} analyses available for 11 years (2000-2010). However, it implies that the ratio between PM_{10} and $PM_{2.5}$ is well captured by the models, which remains challenging because of the highly variable contribution of sea salt and dust. On average over Europe, $PM_{2.5}$ makes up to 76% of PM_{10} in the raw models. In the analyses, this fraction is only 63%, which is also closer to the observation estimates reported by (De Leeuw and Horálek, 2009). Therefore, this approach will likely overestimate $PM_{2.5}$.

Figure 3 shows the long-term evolution of $PM_{2.5}$ exposure applying both approaches on country averaged population weighted estimates to reconstruct proxy $PM_{2.5}$ exposure over the whole period. The raw and data fused time series of PM_{10} and $PM_{2.5}$ are also shown. Raw PM_{10} and $PM_{2.5}$ time-series simulated by CTMs display the usual underestimation of PM, the analysed averages are therefore substantially higher for both $PM_{2.5}$ and PM_{10}. The analysed $PM_{2.5}$ average is lower for 2007 than for later years, although the trend is opposite both in the raw models and in the PM_{10} analyses. Considering the lower number of stations included in the data fusion for $PM_{2.5}$ in 2007, an artefact of this data coverage may exist, therefore 2007 is excluded in the analysed $PM_{2.5}$ EDT fields in the report.

The two methods to reconstruct proxy-adjusted $PM_{2.5}$ data for the whole period are also displayed in Figure 3. As expected, the proxy based on PM_{10} (method 2) is 13% higher, but the difference is constant in time so that there is no impact on the trend. Nevertheless, in order to avoid such an overestimation, we will rely on method 1, where $PM_{2.5}$ is corrected from the bias over the 2008-2009-2010 years. This ratio is then applied to each individual model participating to the EDT ensemble so that the envelopped of unbiased models can be presented.

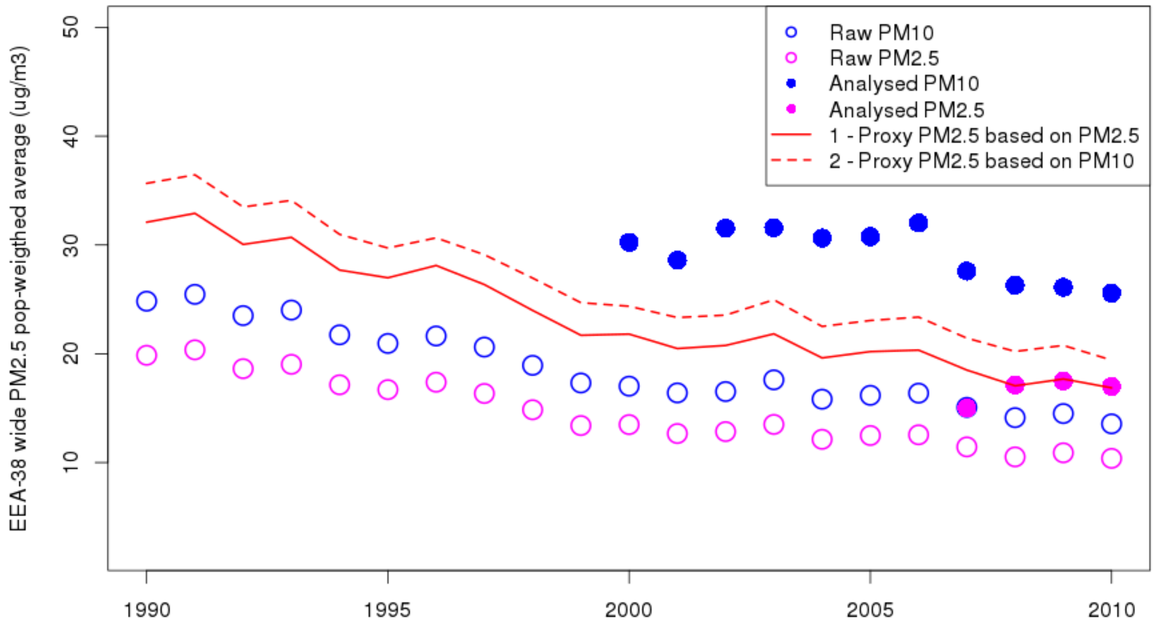


Figure 3: Europe-wide average population-weighted PM concentrations in the EDT dataset for raw (1990-2010) and analysed (2000-2010 for PM_{10} and 2007-2010 for $PM_{2.5}$) model ensembles. Proxy corrected $PM_{2.5}$ concentration for the period (1990-2010) based on two correction strategies are also presented.

2.1.3 Copernicus Atmospheric Monitoring Service

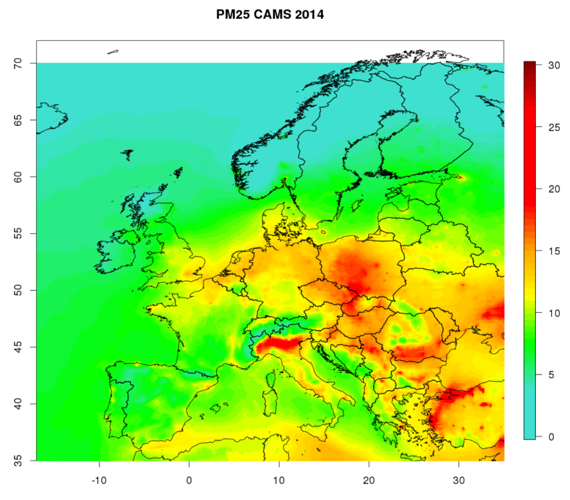
The Copernicus Atmospheric Monitoring Service (CAMS) produces annual maps of ambient particulate matter pollution. CAMS is a Service of the European Commission that follows-up from earlier Framework Programme MACC (Monitoring Atmospheric Composition and Climate) research projects. More details on model setup and performances are available on the CAMS Policy Support website[7].

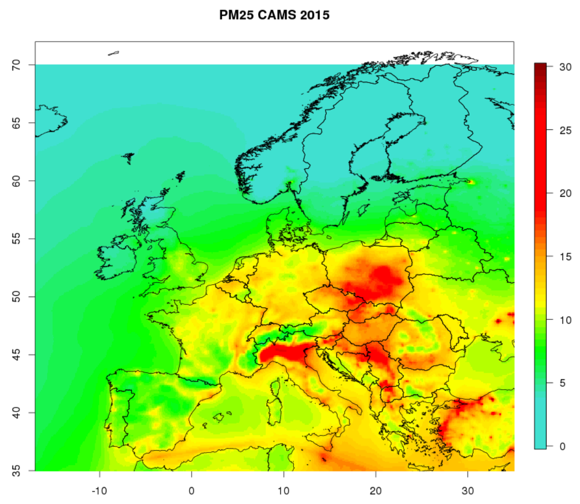
[7] http://policy.atmosphere.copernicus.eu/Reports.html, last accessed 26 July 2017

The present report limits the analysis to the ensemble of Regional CAMS CTMs: CHIMERE, EMEP MSC-W, EURAD, LOTOS-EUROS, MATCH, MOCAGE and SILAM. All of them include either data assimilation or data fusion techniques to produce annual mean $PM_{2.5}$ concentration maps (Figure 4). Air quality e-reporting data are used to improve the model outputs, although it should be stressed that only a fraction (about two-thirds) of the database is used in the assimilation process, while the remainder is kept for validation purposes. As such, the CAMS products differ substantially from the other data sources included in the present report that use all the available data. The assimilation and fusion techniques differ between the participating models e.g. 3D var, 4D var, Ensemble Kalman Filter, or optimal interpolation relying on kriging with an external drift (Marécal et al., 2015).

The list of CTMs, versions and setups that are included in the CAMS ensemble composite may change from year to year with the development of fusion and assimilation techniques for $PM_{2.5}$ concentration. All model results are corrected with validated observations, except for 2016 where the interim analysis was used, which relies on up-to-date (and therefore not validated) data.

- Regional CAMS-VRA (Validated analysis)
  - 2014: CHIMERE, EMEP MSC-W, EURAD, LOTOS-EUROS, MATCH, SILAM
  - 2015: CHIMERE, EMEP MSC-W, EURAD, LOTOS-EUROS, MATCH, MOCAGE, SILAM
- Regional CAMS-IRA (Interim analysis)
  - 2016: CHIMERE, EMEP MSC-W, EURAD, LOTOS-EUROS, MATCH, MOCAGE, SILAM





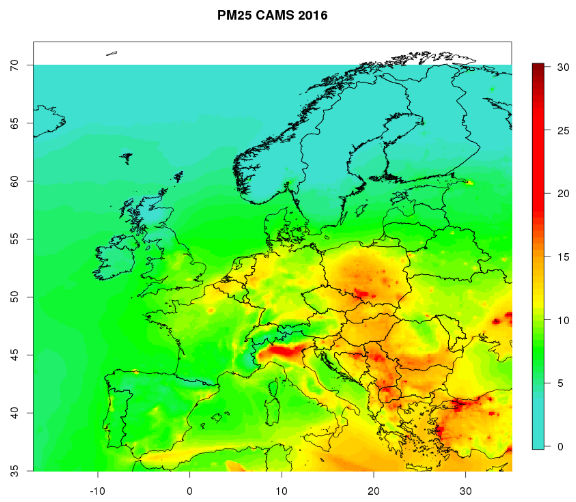


Figure 4: Maps of annual mean $PM_{2.5}$ (µg/m^3) concentrations in the ensemble CAMS regional reanalyses for the period 2014-2016. Note that the number of CTMs vary from year to year.

2.1.4 Global Burden of Disease and World Health Organization

The Global Burden of Disease has developed an alternative methodology to derive a global map of surface $PM_{2.5}$ concentrations at a resolution of 0.1° x 0.1° of longitude and latitude. This methodology is also sometimes used by the World Health Organization. The details are presented in (Brauer et al., 2016), although there are ongoing improvements of this technique as presented in (Shaddick et al., 2016).

The methodology relies on a combination of satellite retrievals, in situ surface measurements and chemistry transport modelling. The satellite data are column integrated aerosol optical depth (AOD) that is only available as total vertical column without any information about the vertical distribution. Since CTMs can model both surface concentrations and altitude optical properties, such a model (GEOS-Chem in the present case) is used in the spatially and temporally dependent regression between satellite and surface measurements. Whereas the regression to convert AOD to surface $PM_{2.5}$ was originally performed on a country basis (therefore introducing sharp discontinuities at the country boundaries), a forthcoming revised algorithm will provide a more continuous estimate.

The satellite AOD estimates are those of the MODIS, MISR and SeaWifs spaceborne instruments, which include global coverage at a resolution of about 10 km since the early 2000s (Brauer et al., 2016). The main added value of using satellite information lies in reaching out to areas poorly covered by regular monitoring networks. Using a better spatial coverage also allows to minimise the bias of air quality monitoring networks, which are often more dense in polluted areas, therefore leading to an overestimation of average exposure. Note however that this effect should be minimized in Europe thanks to the siting criteria defined in the 2008 Air Quality Directive (EC, 2008).

In the GBD13 version it was decided to reconstruct historical exposure from a correction of satellite maps involving models and in situ observation for earlier years independently. But in GBD15 it was prefered to use a calibration for a recent year, and not using models for the historical period. The reconstruction of the temporal trend is therefore substantially different.

In the GBD13 methodology, CTMs are not only used for the calibration of satellite data, they are also used to assess the temporal trend, in particular for earlier years, in the 1990s. While GEOS-CHEM is used for the regression between surface PM and AOD column, the trend is retrieved from TM5 simulations, using the

same anthropogenic emission inventory as used in the Eurodelta-Trends exercise (ECLIPSE), see details in (Brauer et al., 2016). It is an important difference with GBD15, where the trend comes exclusively from observations without involving any modelling.

Figure 5 shows the map of $PM_{2.5}$ concentrations for the year 2014 provided by the WHO[8], therefore using the GBD15 methodology.

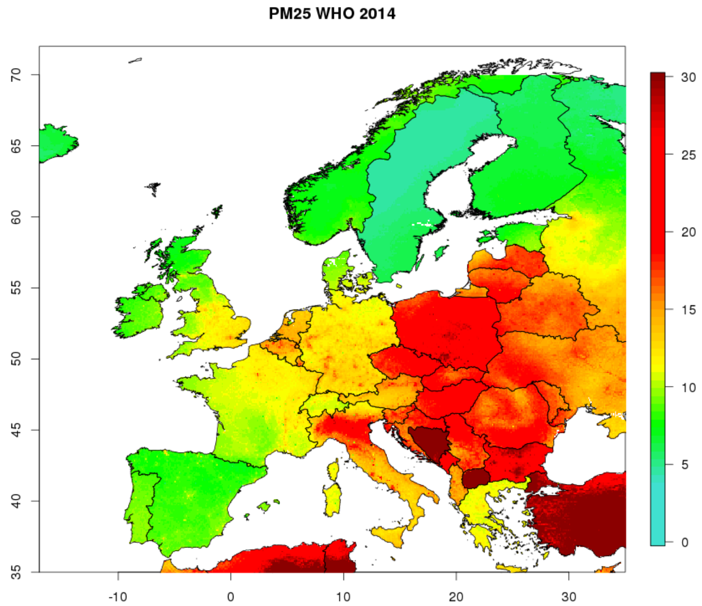


Figure 5: $PM_{2.5}$ ($\mu g/m^3$) concentration map for 2014 provided by the World Health Organisation using the GBD15 methodology based on data fusion of satellite and in situ observations as well as model results.

2.2 Population

For consistency purposes, we use a single set of population data throughout the exposure assessment (with an exception for the GBD data as explained in Section 3.1). The gridded population maps were provided by the Czech Hydro Meteorological Institute (CHMI) and described in the ETC/ACM Technical Report 2016/6 (Horálek et al., 2016). They consist of population data at 1-km horizontal resolution based on the Geostat 2011 grid dataset[9].

For regions not included in the Geostat 2011 maps, alternative sources were used. Primarily, JRC (Joint Research Centre) population data at a resolution of 100x100 m (Gallego, 2010), which was spatially

[8] http://who.int/phe/health_topics/outdoorair/databases/modelled-estimates/en/, last accessed 26 July 2017.
[9] European Commission (Eurostat, Joint Research Centre and DG Regional Policy - REGIO-GIS), http://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/population-distribution-demography, last accessed 24 July 2017

aggregated into the reference 1x1 km EEA grid[10]. For regions that are neither included in the Geostat 2011 nor in the JRC database, the population density data from the ORNL LandScan Global Population Dataset[11] was used. This dataset is at 30x30 arcsec resolution; its values are based on the annual mid-year national population estimates for 2008 from the Geographic Studies Branch, US Bureau of Census[12]. The ORNL data is re-projected and converted from its original WGS1984 30x30 arcsecs grids into EEA's reference projection ETRS89-LAEA5210 at 1x1 km resolution by EEA.

The areas lacking Geostat 2011 data, and supplemented with JRC or ORNL data were: Gibraltar (JRC), Faroe Islands, British crown dependencies (Jersey, Guernsey and Man) and Northern Cyprus (ORNL). As such, the Geostat 2011 1x1 km data and these supplements cover the entire area of the EEA member and cooperating countries.

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[10] EEA version popu01clcv5.tif dated 24 Sep 2009, http://www.eea.europa.eu/data-and-maps/data/population-density-disaggregated-with-corine-land-cover-2000-2, last accessed 24 July 2017
[11] Oak Ridge National Laboratory LandScan high resolution global population data set. http://www.ornl.gov/sci/landscan/landscan_documentation.shtml, last accessed 24 July 2017
[12] http://www.census.gov

3 Average $PM_{2.5}$ exposure

3.1 European and country average exposure

Exposure to ambient $PM_{2.5}$ concentrations is assessed from the population-weighted average $PM_{2.5}$ concentrations by country.

The ETC/ACM population maps are combined to the ETC/ACM, EDT and CAMS data sets of ambient $PM_{2.5}$ concentration fields to obtain population-weighted aggregates. The ETC/ACM 1 km population raster is projected onto the native grid of each source of ambient $PM_{2.5}$ concentrations. Then, the $PM_{2.5}$ grid is combined with a shapefile of country boundaries to assess the fraction of the grid cell belonging to the corresponding country.

For GBD13 and GBD15 population weighted country averages there is a slight risk of inconsistency in the spatial allocation of population data. Whereas we use Geostat information to compute population weighted concentrations for ETC/ACM, EDT and CAMS $PM_{2.5}$ concentrations (see Section 2.2), the GBD15 uses Global Gridded Population of the World data set version 3.0 (GPW v3.0)[13] provided for 1990, 1995, and 2000, and projected (in 2004, when GPWv3 was released) to 2005, 2010, and 2015. GPW uses satellite night time light images to allocate population, whereas Geostat is based on land use information. We note however that this risk of discrepancy is limited to changes in the spatial distribution of the population, because a scaling to the total population of Geostat was applied to GBD13 and GBD15 data.

For the 1990-2015 time-period, population-weighted $PM_{2.5}$ concentrations aggregated by country are provided through the State of Global Air project on the Health Effects Institute (HEI) website[14]. These data rely on the latest revision of the exposure methodology used in the Global Burden of Disease 2015 (GBD15) (Cohen et al., 2017). An earlier version (GBD13) is also available from the supplementary material of (Brauer et al., 2016).

The list of countries included here are EEA 39 except Turkey: Albania, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Kosovo under United Nations Security Council Resolution 1244/99, Latvia, Lithuania, Liechtenstein, Luxembourg, the former Yugoslav Republic of Macedonia, Malta, Montenegro, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Serbia, Sweden, Switzerland, and the United Kingdom. Note that for Kosovo under United Nations Security Council Resolution 1244/99 we used the same country average population $PM_{2.5}$ exposure estimate as for Serbia, but mortality estimates are scaled according to the relative population of Kosovo and Serbia (as retrieved from (EEA, 2017) for the year 2014). For Lichtenstein, since no health information is available in the WHO database, gap-filling was performed with a neighbouring country: Austria.

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[13] http://sedac.ciesin.columbia.edu/data/collection/gpw-v3, last accessed 26 July 2017
[14] State of Global Air 2017. HEI, 2017. www.stateofglobalair.org. Data source: Global Burden of Disease Study 2015. IHME, 2016. (Accessed 26 July 2017).

3.2 Comparison of exposure series

The various data sets of exposure series are plotted in terms of average population-weighted exposure over the whole of Europe[15] in Figure 6. Equivalent series for individual countries as well as maps of country average population exposure (Figure 19) are provided in the Annex of this report. Note that the WHO estimate for 2014 is not included as it is identical to the GBD15 value for that year.

Even though all datasets make use of in-situ observations, there is a substantial spread in average exposure to $PM_{2.5}$. The main reasons for these differences are:

- While both GBD13 and GBD15 use chemistry-transport models for the regression between surface PM and AOD columns, only GBD13 includes also models to assess the temporal evolution over 1990-2010 while GBD15 relies exclusively on observations. As a result, the trend is different: the relative decrease in 2010 compared to 1990 is lower for GBD15, ca. 26%, than for GBD13, ca. 40%.
- CAMS do not include the whole AQ e-reporting in the data assimilation process since about 1/3 of the database is kept for validation purposes. In addition, estimates were produced with different versions and combinations of models for each individual year (see 2.1.3). Unlike the other estimates that are reanalyzed products, there was no attempt to produce a consistent trend. Rather, all the possible methodological improvements were implemented from year to year. Last, the data used for 2016 are interim reanalysis relying on up-to-date (therefore not validated as for 2014 and 2015) in situ measurements included in the model assimilation and fusion process.
- The estimation of the average exposure to $PM_{2.5}$ from individual CTMs, in both the EDT and CAMS ensembles, are of the same order as the discrepancy amongst the different data sets for exposure. For example, the variability of models within a given ensemble (either EDT or CAMS) is similar to the variability between the various data sets (ETC-ACM, GBD, average of Eurodelta-Trends models or the average of CAMS models).

However, Figure 6 shows some robust features. The overall picture indicates a substantial downward trend for the average exposure to $PM_{2.5}$, especially over the 1990-2010. ETC/ACM and GBD15 report a somewhat flat trend between 2005 and 2015 that would need to be further investigated. Whereas the spread is very large in the early 1990s, the values are converging in the most recent period (2014-2015).

Figure 7 shows EDT, CAM-VRA and GBD15 estimates for each country plotted against those of ETC/ACM. The first panel with EDT and GBD15 refers to the year 2010, while the second one with CAMS-VRA and GBD15 refers to the year 2015. It can be noted that the vast majority (the only exception being for Latvia and Lithuania for GBD15 in 2015, with an even higher difference) are within 50% differences with respect to ETC/ACM, which remains a high dispersion.

[15] EEA 39 except Turkey, as explained in the previous paragraph.

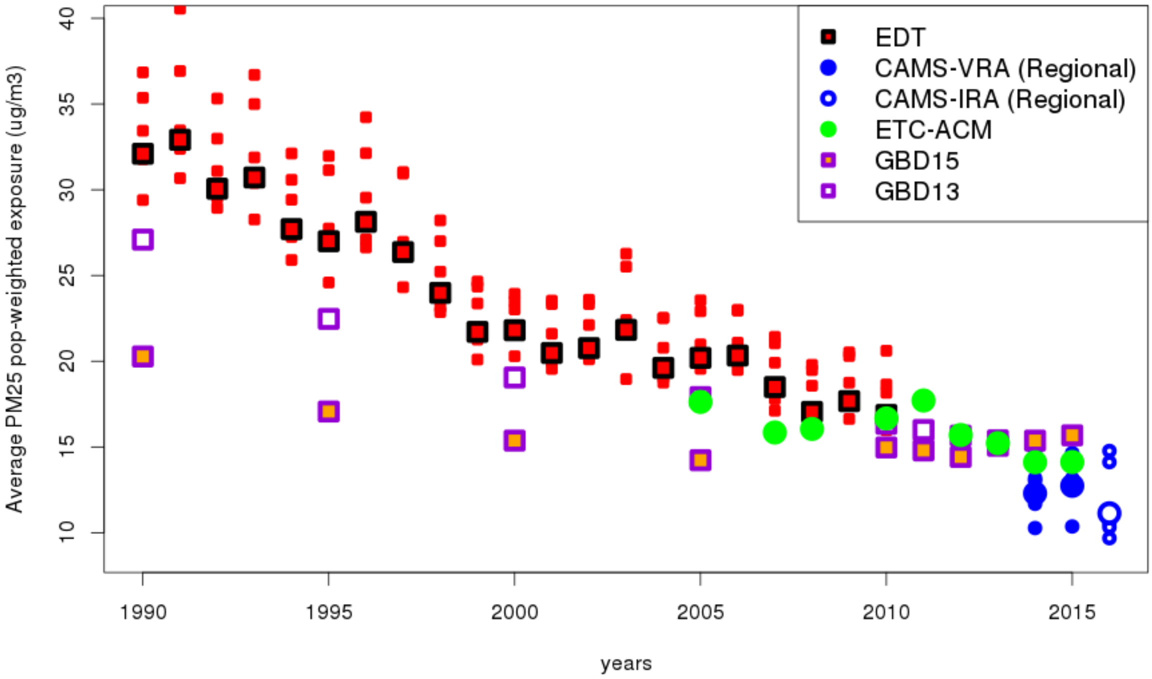
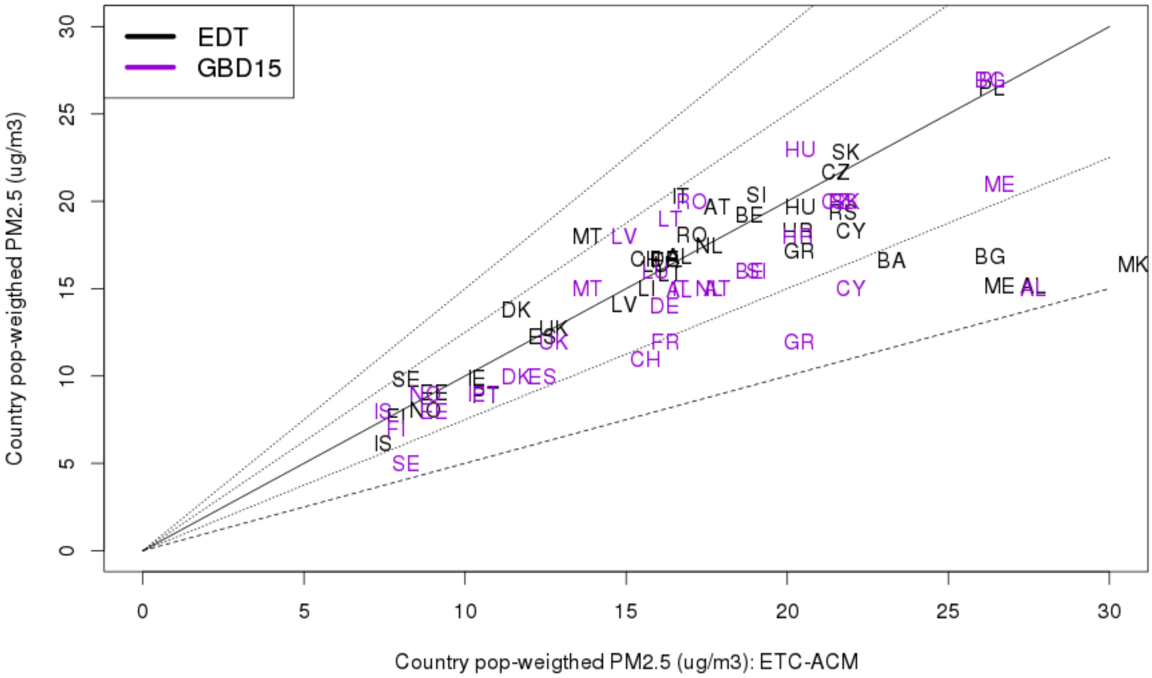


Figure 6: Average exposure to $PM_{2.5}$ (as population weighted concentrations, µg/m^3) in Europe over the 1990-2016 period from various data sets of $PM_{2.5}$ concentrations: Eurodelta-Trends (EDT), Copernicus Atmospheric Monitoring Service (CAMS Regional Validated and Interim reanalyses: VRA and IRA), European Topic Centre on Air Pollution and Climate Change Mitigation (ETC/ACM), and Global Burden of Disease (GBD, versions 2013 and 2015). For CAMS and EDT, individual participating models are displayed (smaller red and blue dots) as well as the ensemble median in the corresponding colour.

For 2010, EDT estimates higher than +/- 25% compared with ETC/ACM regard the eastern Mediterranean and Balkan countries: Albania (AL), Bosnia and Herzegovina (BA), Bulgaria (BG), Montenegro (ME), TFYR Macedonia (MK) as well as very small territories such as Malta (MT). For that year, GBD15 displays also important differences (underestimations) for Albania (AL), Switzerland (CH), Cyprus (CY), France (FR), Greece (GR), and Sweden (SE).

The pattern of the scatter plot differs substantially for GBD15 between 2010 and 2015, with higher average exposure to $PM_{2.5}$ than ETC/ACM in 2015 for most countries, especially towards Nordic and Baltic countries such as Estonia (EE), Finland (FI), Iceland (IS), Lithuania (LT), Latvia (LV), or Norway (NO), but also Ireland (IE) and Luxembourg (LU). For CAMS, the comparison is done for 2015, the latest year using validated data in the assimilation. CAMS displays a general underestimation compared with ETC-ACM, especially in Eastern Europe: Albania (AL), Bulgaria (BG), Montenegro (ME), TFYR Macedonia (MK), but also Iceland (IS).



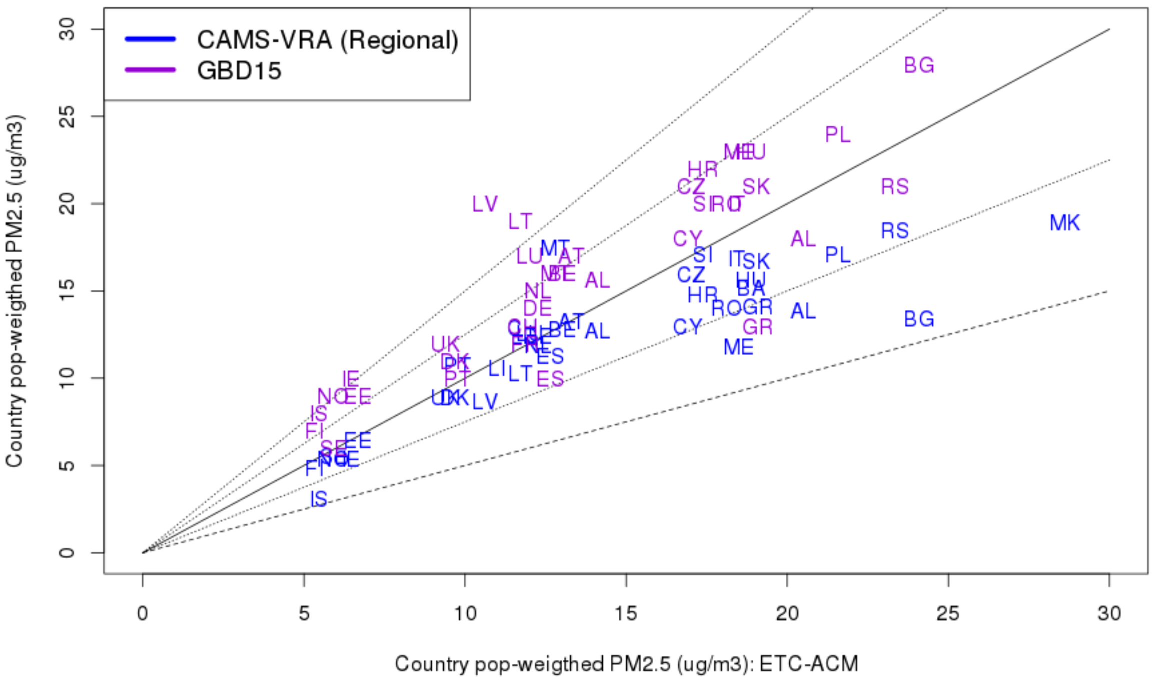


Figure 7: **Scatterplot between country average exposure (as population weighted estimates, µg/m^3) comparing ETC/ACM maps (x-axis) against EDT and GBD15 (y-axis) for 2010 (top), and against CAMS and GBD15 (y-axis) for 2015 (bottom). Dotted and dashed lines are for +/- 25% and +/- 50% differences respectively.**

4 Health impact trends

4.1 Methodology

The quantification of health impacts relies on the INERIS version of the health impact assessment (HIA) framework Alpha-RiskPoll (ARP; developed by EMRC, and described in (Schucht et al., 2015)). The HIA tool ARP is regularly used in European Policy analyses such as the CAFE (Clean Air For Europe) programme. ARP uses the methods for benefits assessment that were first developed under the EC funded ExternE project (External cost of Energy[16]) during the 1990s. These methods are extensively documented in (Holland et al., 2005a;Holland et al., 2005b;Holland et al., 2005c;Holland et al., 2011) and (Hurley et al., 2005). They have been applied since the end of the 1990s to cost-benefit assessments of EC and UNECE[17] policies and were thoroughly reviewed (Krupnick et al., 2005;WHO, 2013a, b). The current version of the model implements the methodology update recommended by the WHO/Europe review «Health Risks of Air Pollution in Europe» (HRAPIE) (WHO, 2013b, a), which is described in (Holland, 2014a, b). Recommendations made in HRAPIE and applied in ARP regard the Concentration-Response Functions (CRFs) linking levels of pollutant exposure to a set of specific health endpoints (mortality and different morbidity impacts).

The health endpoint mortality due to chronic exposure to $PM_{2.5}$ is calculated for the age-group above 30 years based on the recommended Relative Risk (RR) of 1.062 for a 10 µg/m^3 increase of $PM_{2.5}$ (95% confidence interval is 1.040-1.083). Mortality effects are calculated for all-cause (natural) mortality, as linear functions and in response to a one-year pulse change without lag, without any threshold for $PM_{2.5}$ concentrations. Following the WHO advice, all particles matter are treated as equally harmful, irrespective of source and chemical composition since a precise quantification of the health effects of individual PM components is not possible according to current knowledge (Miller et al., 2011;WHO, 2007, 2013a, c;COMEAP, 2015).

In the present study, the use of ARP is restricted to quantifying one health endpoint, the mortality from chronic (long-term) exposure to $PM_{2.5}$, expressed in two metrics, the premature deaths and the years of life lost (YOLL), presented on an annual basis. By using the HRAPIE methodology, the present health outcomes are coherent with those described in (De Leeuw and Horálek, 2016) and in the EEA´s Air Quality in Europe reports (EEA, 2017).

Consistency with (EEA, 2017) was further assured by using up-to-date population and health data. Population data (total and age class specific population data) relies on the UN's World Population Prospects, 2017 Revision[18]. Information on mortality (all-age natural deaths, and 30+ years natural deaths) were extracted (and calculated) from the WHO Mortality Database[19] (ICD-9 and ICD-10 classification, March and October 2017 updates, respectively). For a given country, the age distribution is assumed to be the same in all grid cells. For countries where this data was not available, a gap filling was performed using data from the latest available year.

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[16] http://www.externe.info/externe_d7/
[17] United Nations Economic Commission for Europe.
[18] https://esa.un.org/unpd/wpp/Download/Standard/Population/
[19] http://www.who.int/healthinfo/mortality_data/en/

There are some differences in the data sources compared to (De Leeuw and Horálek, 2016). These authors used age-class specific population data from an earlier UN World Population Prospect (2015), total population from Eurostat (2015), and mortality data from an earlier version of the WHO dataset (July 2016). Furthermore, while they estimated missing data for Andorra, Monaco and San Marino from data of neighbouring countries, we decided to exclude these countries because they are not included in the list of EEA39 countries. For Kosovo, under UNSCR 1244/99, a similar approach as De Leeuw and Horálek (2016) was applied based on using the same exposure, baseline mortality and age distribution data as for Serbia, but splitting the total number of deaths attributed to $PM_{2.5}$ according to the relative population of Serbia and Kosovo under UNSCR 1244/99 (the population estimates are then identical to those used in the EEA 2017 Air Quality Report). For Lichtenstein, we did have the relevant exposure estimates (for all data sets except for GBD13 and GBD15) but we used the baseline mortality and age distribution of Austria (as did De Leeuw and Horálek, 2016) and the mortality was scaled according to the population of Lichtenstein.
Nevertheless, overall population estimates used in the present report and in De Leeuw and Horálek (2016) are quite similar: differences of about 0.4% for the EU-28 population for the year 2014.

Whereas we calculate premature mortality in an identical way compared to earlier ETC/ACM work, our model uses a simplified approach for the estimation of YOLL. De Leeuw and Horálek (2016) calculated YOLL from premature deaths. Premature deaths are calculated for 5-year age groups, the number of years of life lost due to premature mortality is then calculated by summing over all age classes the product of the number of deaths in age class *i* attributable to air pollution and the life expectancy at age of death in age class *i* (De Leeuw and Horálek, 2016). In the current study, premature deaths are calculated for the whole population over 30 years, and an estimated RR for YOLL, calculated based on numerous life table runs for Europe by the UK Institute of Occupational Medicine (IOM), is used to calculate YOLL for the total population.

While estimates of premature deaths based on ARP and those presented in EEA (2017) are almost identical for the EU-28 countries (difference of about 1.1 % for the year 2014), the YOLL shows a slightly higher difference (5.7 % higher in ARP compared to EEA for the year 2014) which might be explained by the different methodology used[20].

[20] We consider that the YOLL results from the two methodologies are sufficiently close and do not require an adaptation of our approach here. In addition, in the present analysis we are more interested in relative changes of results over time and between different exposure data sets (all calculated with an identical methodological approach) than in absolute numbers for a specific year.

4.2 Comparison of health impact trends attributable to total $PM_{2.5}$

For each data set of exposure to ambient $PM_{2.5}$ pollution, Figure 8 illustrates the number of premature deaths over the whole of Europe for the 1990 – 2016 period. The estimates for the year 2016 are made with the population and mortality data of 2015 since it represents the latest year with available mortality data. It should be noted that because of the un-even temporal coverage of the various exposure datasets, the data used for various years or time periods differ. We are therefore including all sources on a single plot mainly to provide an envelope of the uncertainty across the various sources of available exposure data. That is why the analysis is divided in two subsections: first we discuss in 4.2.1 the trend over 1990-2010 using a consistent set of exposure data (EDT, GBD13 and GBD15), then we address in 4.2.2 the evolution (total and by country) between 1990 and 2015 using an extended set of exposure data (also involving ETC-ACM and CAMS).

4.2.1 Trend between 1990 and 2010 according to EDT and GBD exposure

The number of premature deaths estimated with EDT, GBD13 and GDB15 data sets for the beginning of the period (1990) varies between 622,114 (GBD15) and 967,793 (median model in the EDT data set). The overall differences between the datasets are just below a factor of 2, which is a very high uncertainty. The various sources of exposure data tend to converge in later years, with a smaller spread in the various available datasets (see Section 4.2.2).

The long term evolution over 1990-2010 is notably different in the GBD15, GBD13 and EDT datasets: -30, -41 and -52%, respectively. These differences are due to the methodological choices. EDT relies exclusively on models for the long term trend, on the contrary GBD15 relies exclusively on observations, while GBD13 is located in the middle and uses a combination of both. It is difficult to give more confidence to either the purely observation or model based estimates. On the one hand, observations suffer from an incomplete coverage of satellite data and a very scarce surface $PM_{2.5}$ monitoring in the 1990s. On the other hand, models suffer from well known shortcomings. It would however be interesting to investigate further this mismatch given the magnitude of the discrepancy. Especially because this discrepancy remains in the 2000´s, with a decrease 10 times larger in EDT (-21%) compared to GBD15 (-2%).

One robust feature which is obtained with all sources of exposure data is the larger improvement of health impact from $PM_{2.5}$ exposure in the 1990s (-35%, -31%, and -25% in EDT, GBD13, and GBD15, respectively) compared to the 2000s (-21%, -13% and -2%) (Table 2).

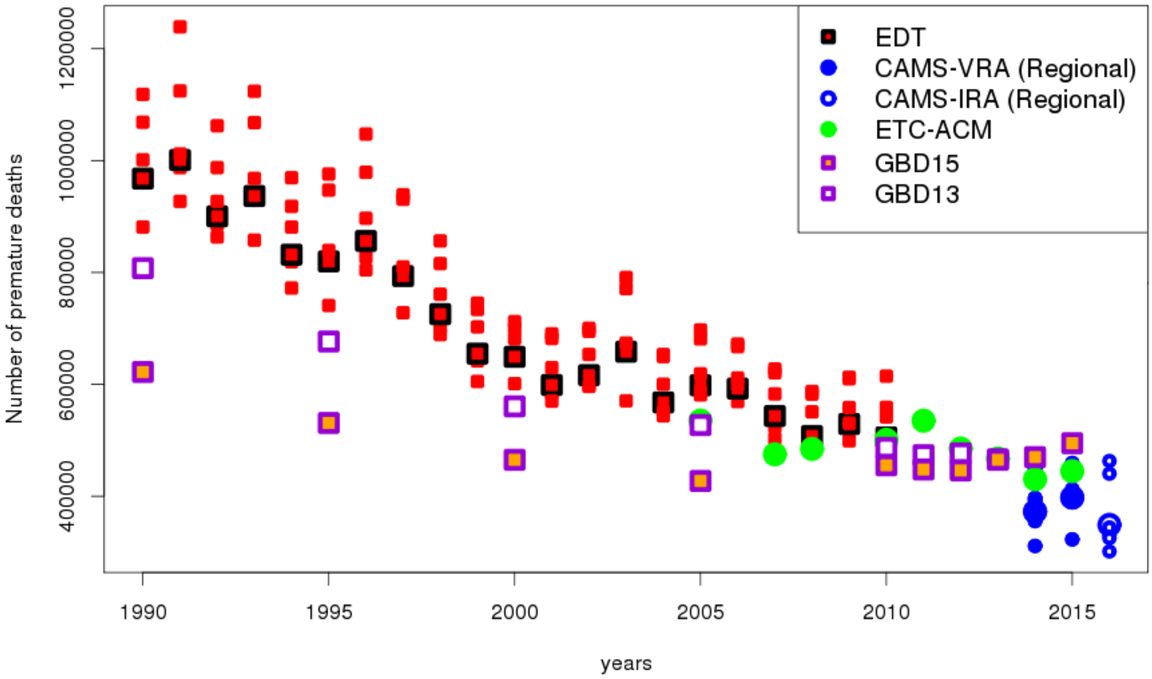

Figure 8: **Premature deaths due to exposure to $PM_{2.5}$ (mortality from chronic, long-term exposure) in Europe over the 1990-2016 period for various data sets of $PM_{2.5}$ concentration: Eurodelta-Trends (EDT), Copernicus Atmospheric Monitoring Service (CAMS Validated and Interim reanalyses: VRA and IRA), European Topic Centre on Air Pollution and Climate Change Mitigation (ETC/ACM), and Global Burden of Diseases (versions 2013 and 2015). For CAMS and EDT, individual participating models are displayed as well as the ensemble median.**

Table 2: **Linear median rates of premature deaths per year attributable to $PM_{2.5}$ for the period 1990 – 2010 according to the EDT, GDB13 and GBD15 exposure data sets. Relative changes for the entire periods are reported in parenthesis.**

Data set		$PM_{2.5}$ EDT/GBD13/GBD15		
Code	**Name**	**1990-2000 Deaths y^{-1}**	**2000-2010 Deaths y^{-1}**	**1990-2010 Deaths y^{-1}**
EDT	Eurodelta-Trends	-34 218 (-35%)	-13 908 (-21%)	-24 863 (-52%)
GBD13	Global Burden of Disease 2013	-24 706 (-31%)	-7 409 (-13%)	-15 833 (-41%)
GBD15	Global Burden of Disease 2015	-15 702 (-25%)	- 979 (-2%)	-8 746 (-30%)

Figure 9 illustrates the calculated linear median rates of premature deaths per year for the 1990 – 2010 period as predicted with the EDT ensemble data set. Higher reduction rates are visible over Germany, Italy,

France, the UK and Poland where larger differences in $PM_{2.5}$ model predictions are also occurring (cf. standard deviations in Table 3). In general, the standard deviation of the EDT data sets is higher in 1990 than in 2010 for most of the countries with a few exceptions (e.g. for Italy, Figure 10).

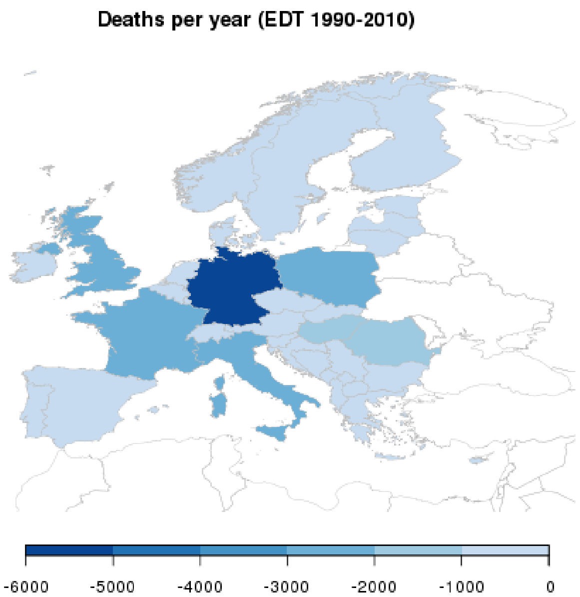

Figure 9: Linear median rates of premature deaths per year in each country in the EDT ensemble for the entire 1990 – 2010 period (total deaths per year).

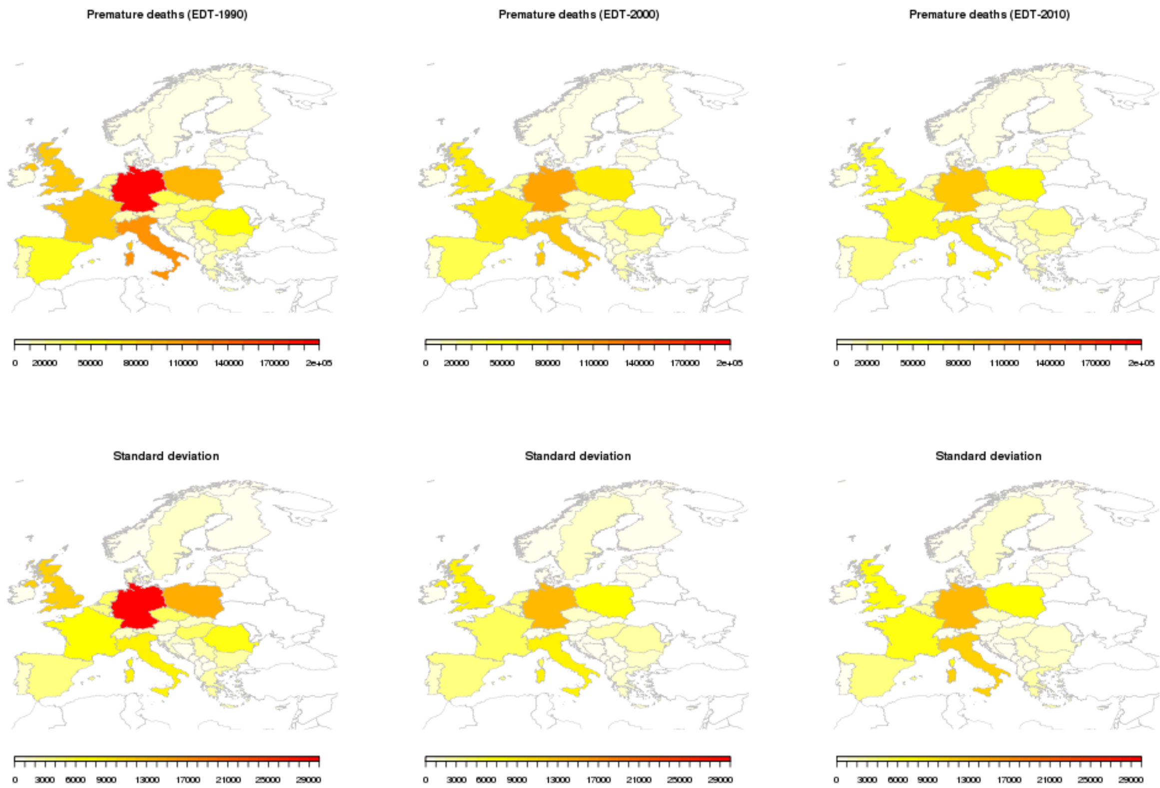

Figure 10: Annual number of premature deaths in each country for the years 1990, 2000 and 2010 in the EDT median ensemble (top panel) together with the standard deviation (bottom panel).

4.2.2 Evolution between 1990 and 2015

Table 3 and Table 4 report the total number of premature deaths as well as the years of life lost (YOLL) for the years 1990 and 2015 and for the countries included in the analysis. These health indicators were estimated using the median of all available datasets (i.e. for 1990: EDT, GBD13 and GBD15 and for 2015: CAMS-VRA, ETC-ACM and GBD15).

Total mortality estimates using all the sources of exposure data range from about 320,000 (CAMS) to 495,000 (GBD15) premature deaths in 2015, so that the uncertainty is substantially reduced compared to the much larger range for 1990 presented in Section 4.2.1. Germany, Italy and Poland were found to be the top-three countries in terms of premature deaths due to chronic exposure to $PM_{2.5}$ with 66,283, 65,811 and 44,903 premature deaths in 2015, respectively[21]. The median number of premature deaths for all the countries is 960,419 ± 169,573 and 444,535 ± 47,738 for the years 1990 and 2015, respectively (Table 3).

[21] It should be noted that we report here estimated premature mortality attributable to air pollution from all available exposure sources. The estimate for 2015 using the same methodology as in previous EEA reports will be published in the Air Quality in Europe - 2018 report later in 2018.

Table 3: Annual premature deaths (median values) and standard deviation attributable to $PM_{2.5}$ for the years 1990 and 2015 using all available data sets (EDT, GBD13 and GBD15 for 1990 and ETC-ACM, CAMS-VRA and GBD15 for 2015).

ISO Alpha-2	Country name	Premature deaths (median*, 1990)	Premature deaths (median*, 2015)	Standard deviation (1990)	Standard deviation (2015)
AL	Albania	2 227	1 183	488	251
AT	Austria	17 308	6 489	3 772	936
BA	Bosnia and Herzegovina	5 462	4 006	1 324	2 209
BE	Belgium	20 895	7 489	5 244	1 185
BG	Bulgaria	21 713	11 016	4 206	3 790
CH	Switzerland	10 785	4 952	2 733	715
CY	Cyprus	716	580	238	130
CZ	Czech Republic	32 615	10 789	5 822	1 851
DE	Germany	177 708	66 283	49 107	7 835
DK	Denmark	8 438	2 935	2 032	414
EE	Estonia	969	668	191	161
ES	Spain	40 940	31 060	9 274	4 039
FI	Finland	3 057	1 600	718	301
FR	France	88 872	35 755	20 358	4 966
GB	United Kingdom	86 872	32 779	14 449	4 650
GR	Greece	15 531	10 490	3 805	2 362
HR	Croatia	10 744	5 174	1 836	761
HU	Hungary	37 468	12 906	6 369	2 079
IE	Ireland	3 273	945	801	289
IS	Iceland	75	52	39	23
IT	Italy	120 622	65 811	25 442	9 704
LI	Liechtenstein	48	23	26	9
LT	Lithuania	4 078	2 848	748	830
LU	Luxembourg	794	271	162	46
LV	Latvia	3 341	1 604	734	664
ME	Montenegro	815	492	120	160
MK	TFYR Macedonia	2 297	2 903	696	1 012
MT	Malta	416	360	160	156
NL	Netherlands	24 488	9 992	6 041	1 334
NO	Norway	3 412	1 359	738	386

PL	Poland	94 165	44 903	16 783	9 977
PT	Portugal	11 486	6 789	2 497	960
RO	Romania	52 426	27 688	8 195	5 996
RS	Serbia***	15 673	3 336	10 226	1 375
SE	Sweden	8 326	3 091	2 674	446
SI	Slovenia	4 017	2 161	939	339
SK	Slovakia	14 792	5 424	3 033	782
XK	Kosovo***	3 958	2 583	842	347
	Median and standard deviation all countries (**)	960 419	444 535	169 573	47 738

(*) Median over the different data sets per country.
(**) Calculation of a) sum over all countries per data set, then b) median over the different data sets totals.
(***) The same exposure and baseline mortality are used for RS and XK, but mortality attributed to $PM_{2.5}$ is split by using the relative population of RS and XK as in (EEA, 2017). The same population data is used for the year 1990 and 2015.

Table 4: Annual years of life lost (YOLL) attributable to $PM_{2.5}$ for the years 1990 and 2015 using all available data sets (EDT, GBD13 and GBD15 for 1990 and ETC-ACM, CAMS-VRA and GBD15 for 2015).

ISO Alpha-2	Country name	Years of life lost (1990) *	Years of life lost (2015) *
AL	Albania	88 096	35 259
AT	Austria	209 696	71 258
BA	Bosnia and Herzegovina	149 231	48 582
BE	Belgium	257 412	88 926
BG	Bulgaria	286 467	98 232
CH	Switzerland	139 699	64 144
CY	Cyprus	13 524	12 412
CZ	Czech Republic	401 811	122 583
DE	Germany	1 961 843	624 778
DK	Denmark	96 078	34 480
EE	Estonia	20 307	7 154
ES	Spain	589 197	333 902
FI	Finland	41 381	18 263
FR	France	1 236 912	451 038
GB	United Kingdom	969 562	380 212
GR	Greece	204 993	112 349

HR	Croatia	151 776	50 374
HU	Hungary	486 774	134 267
IE	Ireland	49 520	16 366
IS	Iceland	1 347	795
IT	Italy	1 542 580	645 196
LI	Liechtenstein	582	248
LT	Lithuania	98 919	28 962
LU	Luxembourg	10 398	4 318
LV	Latvia	70 359	16 320
ME	Montenegro	12 785	6 617
MK	TFYR Macedonia	52 797	41 230
MT	Malta	7 039	5 004
NL	Netherlands	345 396	120 178
NO	Norway	38 690	18 071
PL	Poland	1 544 061	538 404
PT	Portugal	154 278	72 866
RO	Romania	914 359	282 014
RS	Serbia***	232 208	117 302
SE	Sweden	87 923	34 147
SI	Slovenia	64 820	24 508
SK	Slovakia	238 678	75 483
XK	Kosovo***	58 645	29 625
	Median all countries (**)	12 904 776	4 862 997

(*) Median over the different data sets per country.
(**) Calculation of a) sum over all countries per data set, then b) median over the different data sets totals.
(***) The same exposure and baseline mortality are used for RS and XK, but mortality attributed to $PM_{2.5}$ is split by using the relative population of RS and XK as in (EEA, 2017). The same population data is used for the year 1990 and 2015.

By combining all the available data sets of $PM_{2.5}$ concentrations (EDT, GBD13, GBD15, CAMS, and ETC-ACM), the variation in premature deaths for the whole 1990 – 2015 period is also retrieved. Table 5 reports median rates of premature deaths per year as calculated for the 1990 – 2015 period including all the available data sets. The analysed concentration trends for $PM_{2.5}$ indicate that in the period from 1990 to 2015 premature mortality decreased by about 60% (-23 238 deaths per year on average). The slight difference compared to median mortality change between 1990 and 2015 provided in Table 3 (-53%) is due to the fact that we take into account the interannual variability when assessing the trend.

Table 5: Linear median rates of premature deaths per year attributable to $PM_{2.5}$ for the period 1990 – 2015 using all available data sets

ISO Alpha-2	Country name	Deaths y^{-1}*
AL	Albania	-35
AT	Austria	-476
BA	Bosnia and Herzegovina	-51
BE	Belgium	-676
BG	Bulgaria	-279
CH	Switzerland	-269
CY	Cyprus	-5
CZ	Czech Republic	-801
DE	Germany	-5 066
DK	Denmark	-286
EE	Estonia	-28
ES	Spain	-561
FI	Finland	-60
FR	France	-2 305
GB	United Kingdom	-2 719
GR	Greece	-182
HR	Croatia	-222
HU	Hungary	-943
IE	Ireland	-99
IS	Iceland	-0.3
IT	Italy	-2 613
LI	Liechtenstein	-2
LT	Lithuania	-78
LU	Luxembourg	-21
LV	Latvia	-70
ME	Montenegro	-7
MK	TFYR Macedonia	28
MT	Malta	-7
NL	Netherlands	-794
NO	Norway	-97
PL	Poland	-2 077
PT	Portugal	-245

RO	Romania	-1 015
RS	Serbia***	-225
SE	Sweden	-273
SI	Slovenia	-97
SK	Slovakia	-349
XK	Kosovo***	-57
	Median all countries (**)	-23 238

(*) Calculation of a) median over the different data sets per country, then b) linear median fit over the years.
(**) Calculation of a) sum over all countries per data set, b) median over the different data sets totals c) linear median fit over the years.
(***) The same exposure and baseline mortality is used for RS and XK, but mortality attributed to $PM_{2.5}$ is split by using the relative population of RS and XK as in (EEA, 2017). The same population data is used for the year 1990 and 2015.

Figure 11, Figure 12, Figure 13, and Figure 14 show the estimated number of premature deaths due to particulate pollution for the 1990 – 2016 period for each of the countries and data sets included in the analysis. In some cases, at the country level, a larger spread can be observed among the different data sets. Besides, the highest and the lowest concentrations across the countries are estimated by different datasets, without a systematic behaviour. It should be noted that for specific countries like Bosnia and Herzegovina, Serbia and Montenegro, there were important gaps in mortality data (e.g. for Bosnia and Herzegovina only 1990, 1991, 2011 and 2014 mortality data were possible to retrieve, and mortality for intermediate years was estimated using the latest available year) which makes the interpretation of the results rather uncertain. Finally, in the former Yugoslav Republic of Macedonia a slightly increasing trend in premature deaths is found (Table 5). This is triggered by the increase in the $PM_{2.5}$ exposure predicted by the GBD15 exposure dataset (Figure 17). Thus, given the large variability in the predicted $PM_{2.5}$ exposures between the different data sets, no substantial conclusions could be drawn for that country.

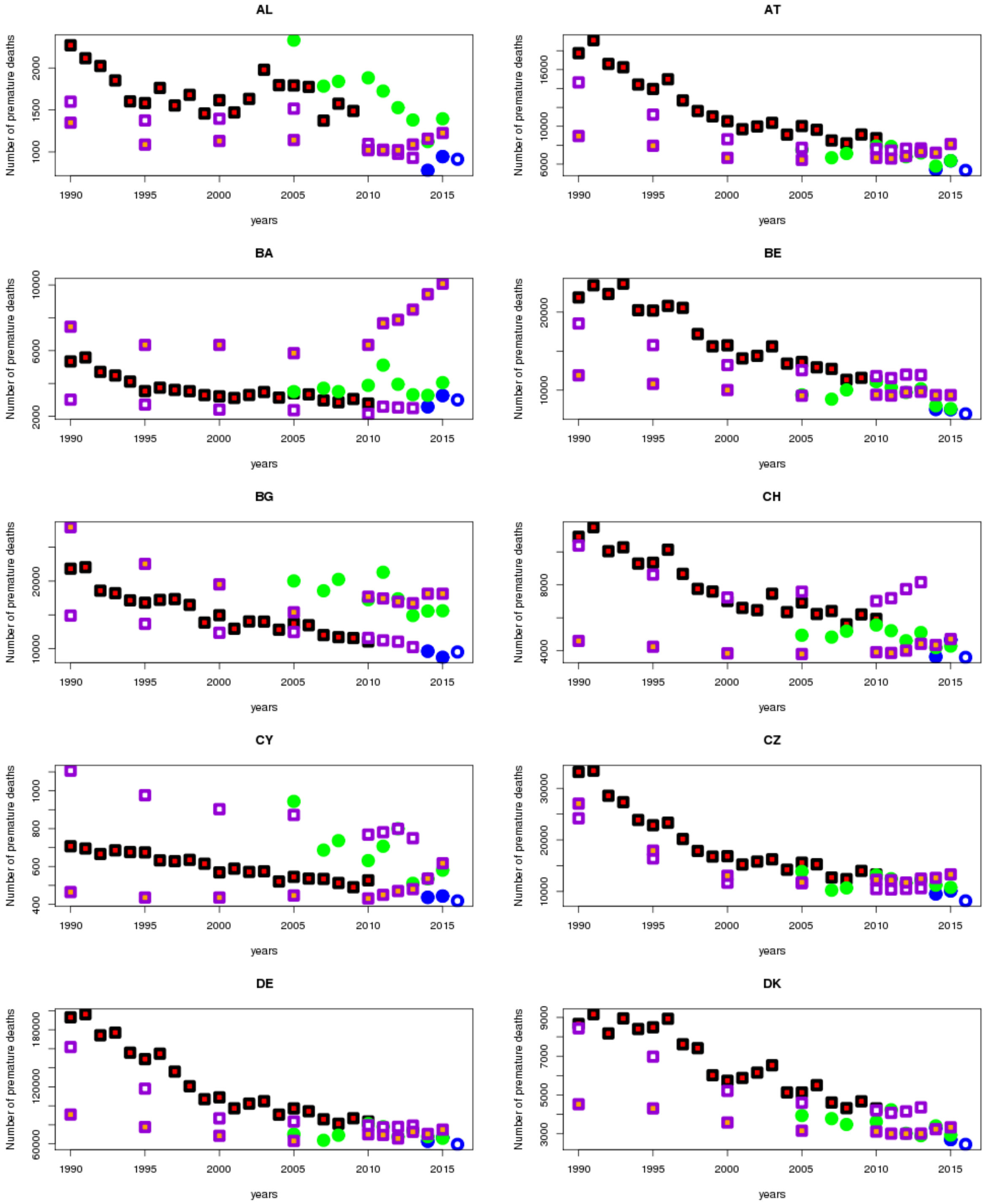

Figure 11: **Country average mortality (premature deaths) over the 1990-2016 period, similar to Figure 8 without individual EDT and CAMS models. See the legend in Figure 14.**

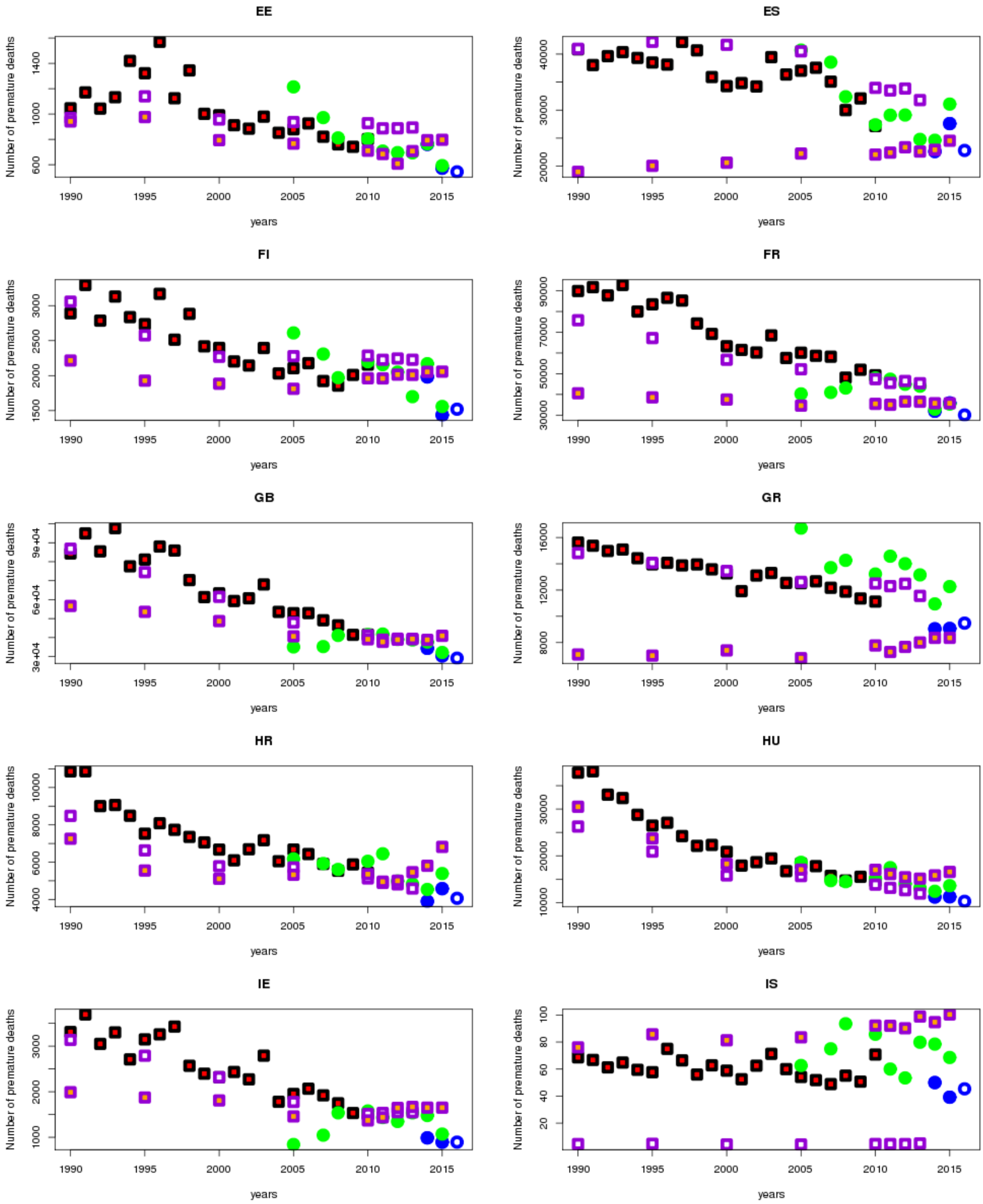

Figure 12: Figure 11 (continued)

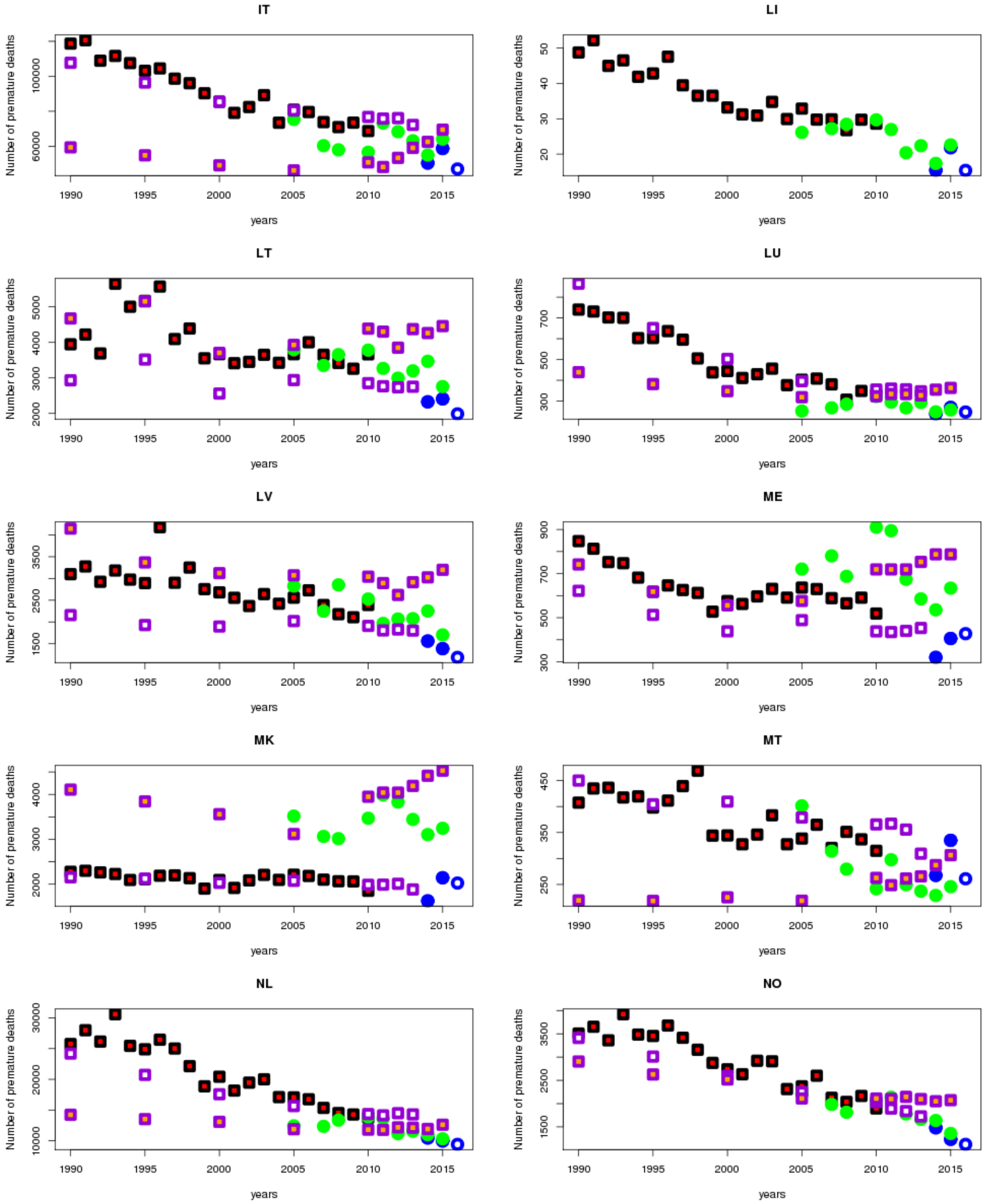

Figure 13: Figure 11 (continued)

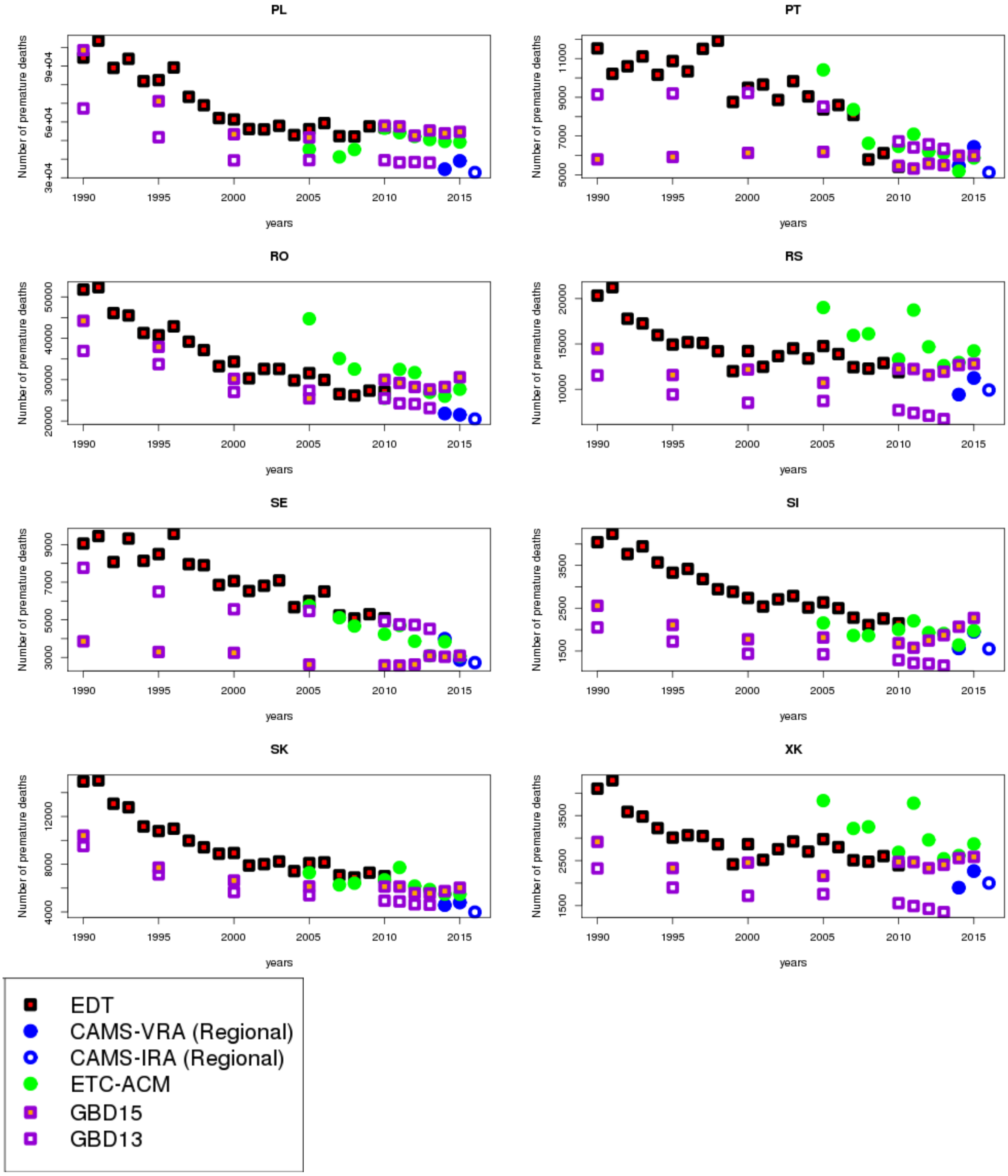

Figure 14: Figure 11 (continued)

5 Conclusions

To assess the long-term evolution in the exposure of the European population to particulate matter air pollution, we investigate various available data sets of $PM_{2.5}$ concentration maps covering at least the whole of Europe (defined here as EEA39 except Turkey) for the period from 1990 to 2016. Different data sets were used:

- The ETC/ACM interpolated maps data set developed by the European Topic Centre on Air Quality and Climate Change Mitigation;
- The EDT (Eurodelta-Trend), a multi-model trend ensemble recently compiled by the EMEP Task Force on Measurement and Modelling;
- The CAMS datasets produced by the Copernicus Atmospheric Monitoring Service (two datasets with either validated data or interim data used in the process of data assimilation and fusion);
- The different data sets developed by GBD (Global Burden of Disease) in both 2013 and 2015 versions and also used by the World Health Organization (WHO).

Based on these data sets, the population exposure to $PM_{2.5}$ concentrations was calculated and used as input data for a health impact assessment tools. The $PM_{2.5}$ concentration data sets were used in combination with age-class specific population data from the UN and mortality data from WHO to perform the analysis.

The number of premature deaths due to chronic exposure to total $PM_{2.5}$ was calculated using the health impact assessment framework Alpha-RiskPoll (ARP) covering the time period from 1990 to 2015 (the year 2016 was also presented although not included in the estimates of long term trends because only the CAMS interim dataset was available for that year).

Comparison between the estimates based on the Alpha-RiskPoll methodology and previous EEA estimates for the EU-28 countries show large agreement for the number of annual premature deaths in Europe overall (the difference is limited to 1%).

Summing over all countries considered in the analysis, total premature deaths due to $PM_{2.5}$ exposure were found to range from about 620,000 to 970,000 in 1990, and from 320,000 to 495,000 in 2015, according to the $PM_{2.5}$ data sets.

For many years, the variability of premature death estimates between the different data sets is around a factor 2, with larger discrepancies at the single country level. The scope of the present work is deliberately limited to assess the uncertainties associated with ambient $PM_{2.5}$ exposure data, but we can point out that uncertainties of the relative risk function are of the same order of magnitude (95% confidence interval of 1.040-1.083).

Despite a spread between $PM_{2.5}$ exposure estimates, all datasets point toward a substantial improvement in health impacts, with a median decrease of mortality of about 60% in Europe between 1990 and 2015, that is an average reduction of about 23,000 death every year. While the health impact of air pollution remain very high in Europe in 2015 with a median estimate of 445 000 death per year in our study, we point out that this number also correspond to more than 500,000 avoided premature deaths per year in 2015 compared to the 1990 situation, where the mortality was 960 000 premature deaths per year.

Another consistent feature in all available long term exposure estimates is the larger improvement over the 1990s than over the 2000s.

There remains however important uncertainties in these estimates. For the period 1990-2010 covered by three long term exposure dataset, the median rates of change for premature deaths per year varies by a factor three (-24 863, -15 833 and -8 746 deaths per year in the EDT, GBD13 and GBD15 data sets, respectively). Since absolute levels are also different, this range results in relative change in premature deaths of -52%, -41% and -30% per year, respectively. These estimates provide a good view of the current state of knowledge and related uncertainties in long term exposure to air pollution but it would be worthwile to investigate the means to provide an independent evaluation of these datasets to reduce the uncertainties.

In the present study, all the different $PM_{2.5}$ components are assumed to be equally harmful to health, since specific dose-response functions for different $PM_{2.5}$ components are, to date, not available. Given that not all the $PM_{2.5}$ components are expected to be equally harmful and, also, not all the $PM_{2.5}$ components are expected to have responded equally to emission reduction strategies in different parts of Europe (i.e. non-linearity effects), future work should look at the evolution of different fine PM components over time. COMEAP (2015) has recently confirmed that both primary and secondary PM are detrimental to health, so reductions of the bulk PM are beneficial to health, and that a better understanding of exposure and health effects is needed before it can be concluded that regulations targeting specific sources or components of $PM_{2.5}$ will better protect public health than the current practice of targeting $PM_{2.5}$ mass as a whole. This also confirms the interest of our analysis of trends in total $PM_{2.5}$ mass and related health effects.

6 Acknowledgements

The ambient particulate matter exposure data used in the present report were provided by:

- The European Environment Agency and its European Topic Centre on Air Pollution and Climate Change Mitigation;
- The Copernicus Atmospheric Monitoring Service operated by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the European Commission;
- The State of Global Air website which is a collaboration between the Health Effects Institute and the Institute for Health Metrics and Evaluation, with expert input from the University of British Columbia;
- The World Health Organization (WHO);
- EURODELTA-Trends Project initiated by the Task Force on Measurement and Modelling of the Convention on Long Range Transboundary Air Pollution. EURODELTA-Trends is coordinated by INERIS and involves modelling teams of BSC, CEREA, CIEMAT, ENEA, IASS, JRC, MET Norway, TNO, SMHI. The views expressed in this study are those of the authors and do not necessarily represent the views of EURODELTA-Trends modelling teams.

The Health and population data were provided by UN and EUROSTAT.

7 Annex

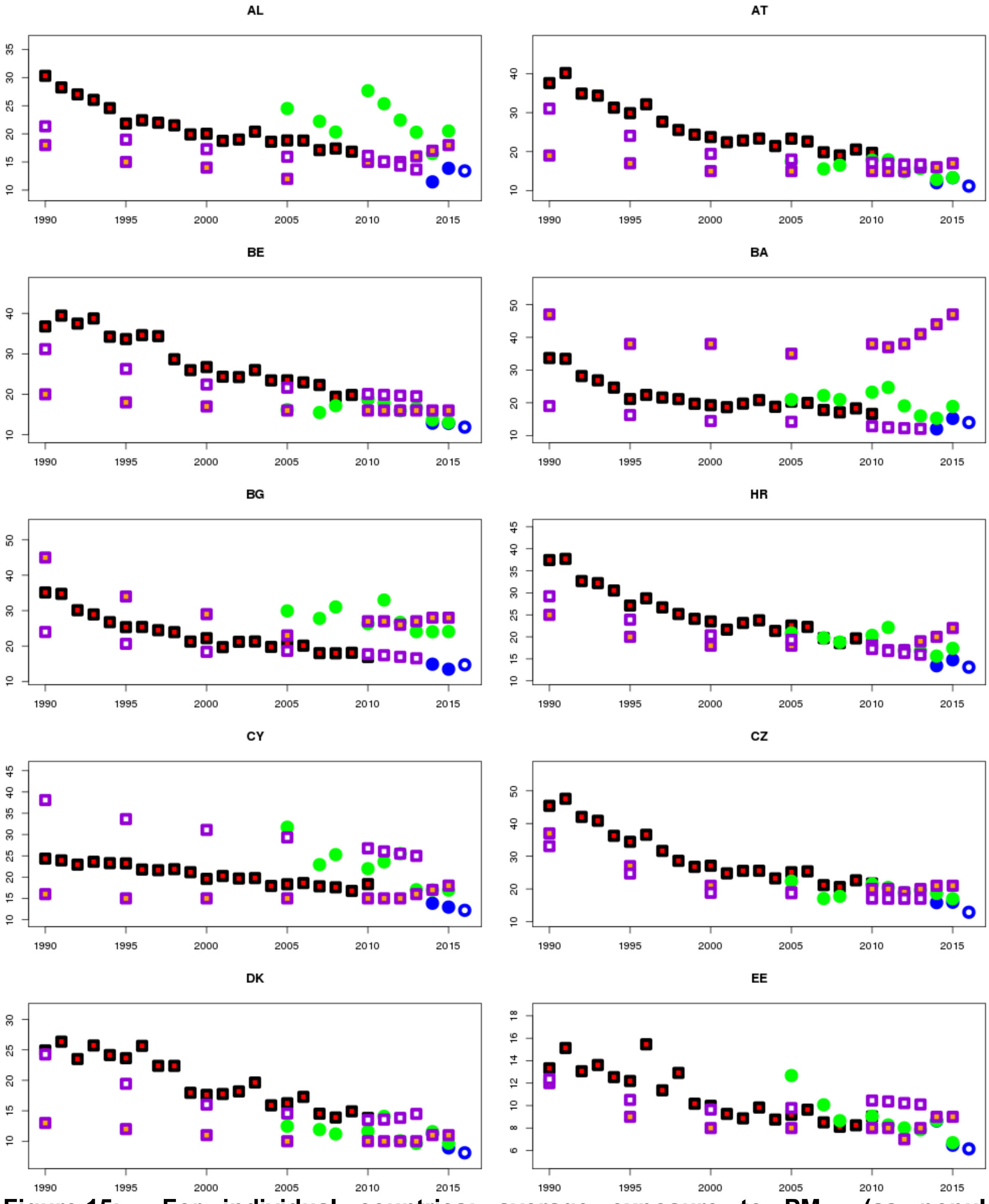

Figure 15: **For individual countries: average exposure to $PM_{2.5}$ (as population weighted concentrations, µg/m^3) in Europe over the 1990-2016 period from various data sets of $PM_{2.5}$ concentration: Eurodelta-Trends (EDT), Copernicus Atmospheric Monitoring Service (CAMS regional Validated and Interim reanalyses: VRA and IRA), European Topic Centre on Air Pollution and Climate Change Mitigation (ETC/ACM), and Global Burden of Diseases (versions 2013 and 2015). See the legend in Figure 18.**

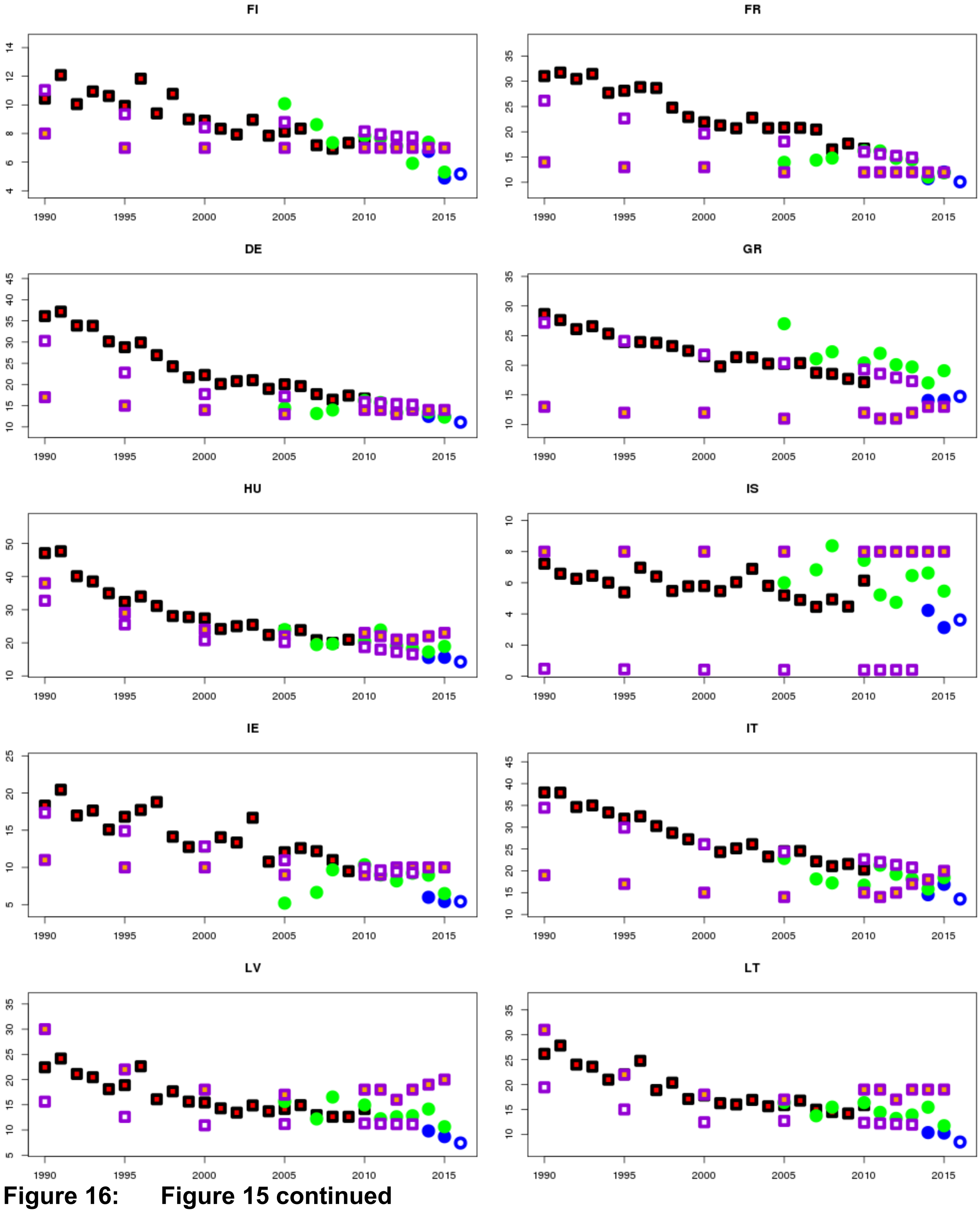

Figure 16: Figure 15 continued

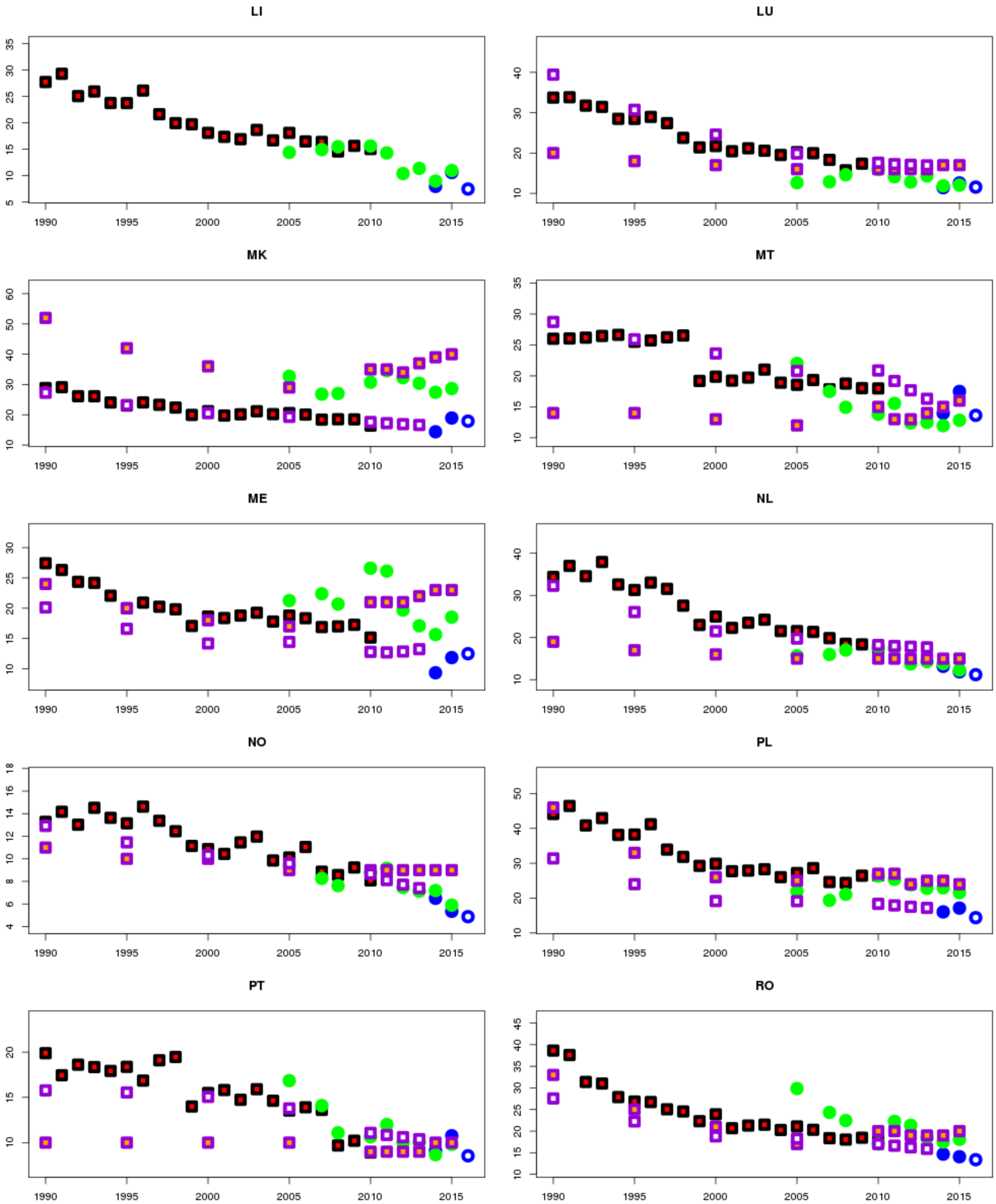

Figure 17: Figure 15 continued

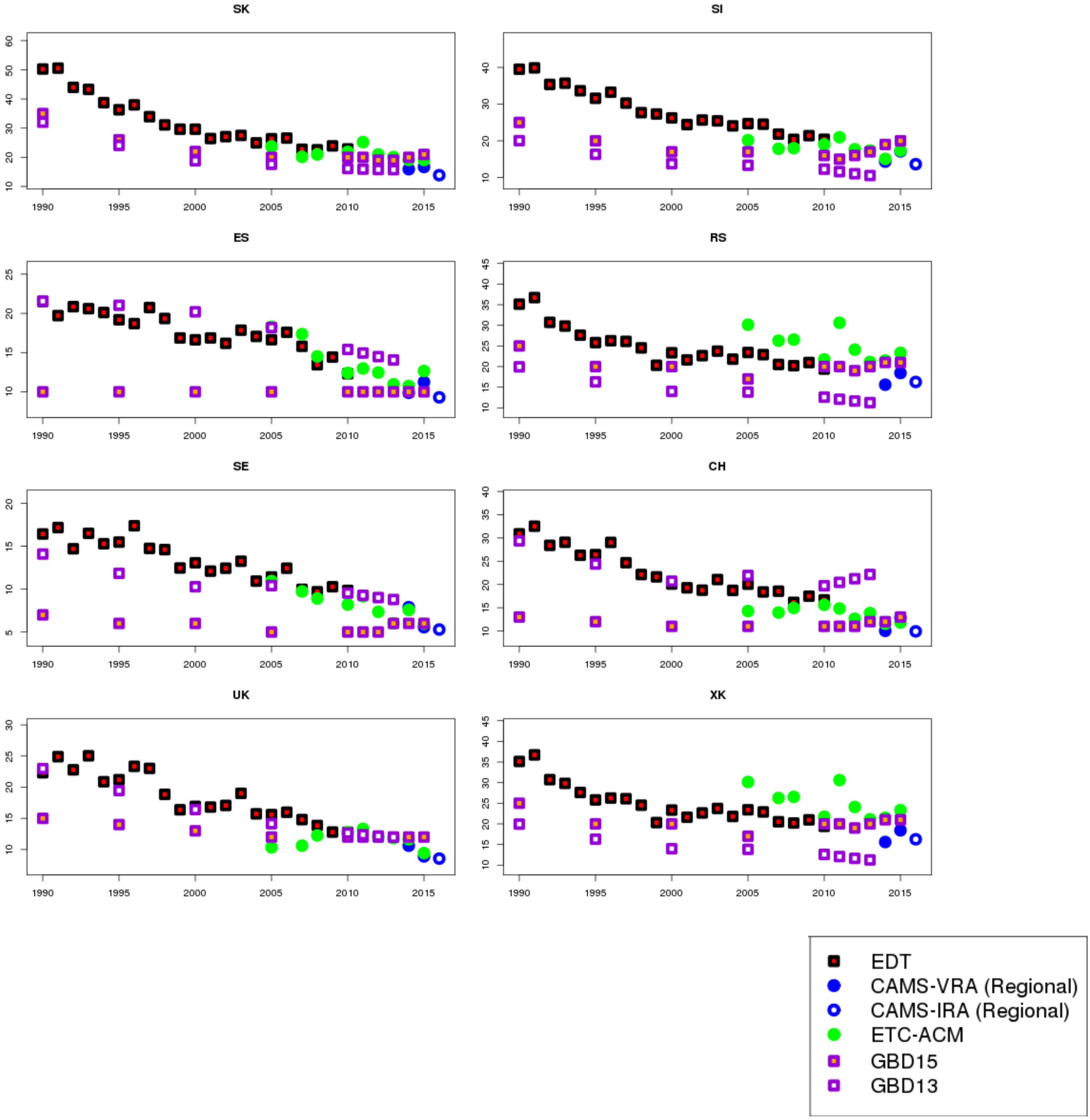

Figure 18: Figure 15 continued

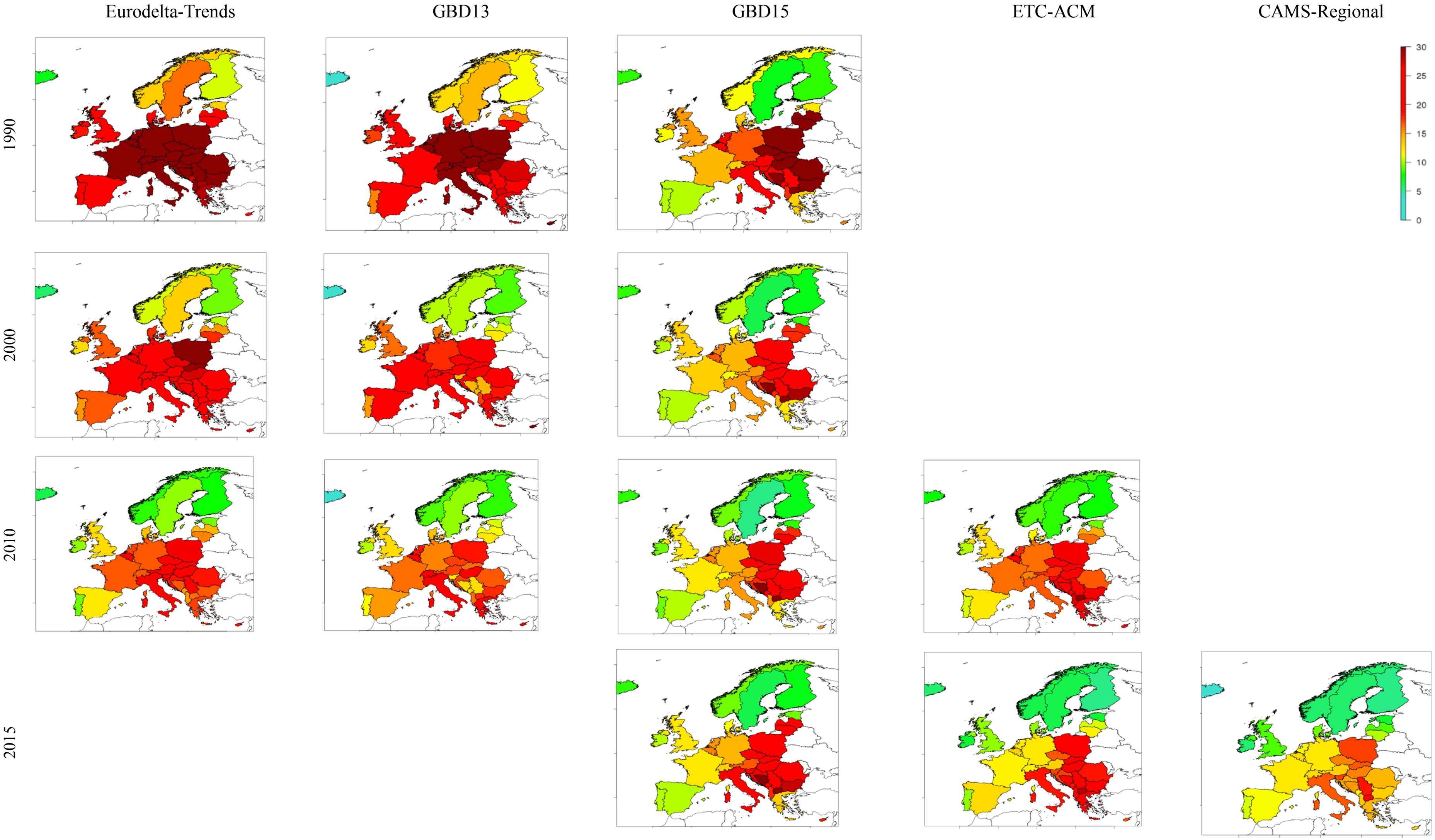

Figure 19: Maps of country-average exposure (population-weighted mean $PM_{2.5}$ concentrations) for 1990, 2000, 2010, and 2015 (top to bottom) according to (left to right) EDT, GBD13, GBD15, ETC-ACM and CAMS-Regional. The colour scale is provided in the top right panel.

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