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Health impacts of atmospheric pollution in a changing climate

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Current annual global estimates of premature deaths from poor air quality are estimated in the range 2.6–4.4 million, and 2050 projections are expected to double against 2010 levels. In Europe, annual economic burdens are estimated at around 750 bn €. Climate change will further exacerbate air pollution burdens; therefore, a better understanding of the economic impacts on human societies has become an area of intense investigation. The MACC project series was a European research effort (2005–2015) addressing monitoring of air pollution. The outcome of this work has been integrated into a European capacity for Earth Observation, the Copernicus Atmospheric Monitoring Service (CAMS). In MACC/CAMS, key pollutant concentrations are computed at the European scale and globally by employing chemically-driven advanced transport models. Combining these efforts with an integrated assessment model for calculating the health impacts and damage costs of air pollution offers a novel and highly multidisciplinary approach with information gained at various spatial and temporal resolutions. These calculations are complementary to other, previous and ongoing efforts to assess health impact projections. It benefits the European community by contributing a novel approach to assess air quality at the local and regional levels, explores new pathways for exploiting earth observational data and benefits to long running EU commitments.

Keywords: pollution, air quality, health, climate change, emissions, transportation, premature death, ozone, particulate matter,

JEL Classification: I100, I310, Q530, R400.

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1. Introduction

Current annual global estimates of premature deaths from poor air quality are estimated in the range of 2.6–4.4 million, and 2050 projections are expected to double against 2010 levels (Horton et al., 2014). In Europe,[1] the economic burden of anthropogenic ambient air pollution has been estimated at around 766 billion Euros (bn €) for the year 2000 (costs in 2006 prices, Brandt et al., 2013). A recent report by the World Health Organisation and the OECD (WHO & OECD, 2015) assessed the economic cost of health impacts from ambient air pollution in the WHO Europe region at around 1,100 bn US$ and 1,300 bn US$ for 2005 and 2010, respectively (based on 2005 costs). The European Environmental Agency (EEA) estimated that industrial emissions as declared in the European Pollutant Release and Transfer Register caused a damage of at least 120–169 bn € in 2009 (EEA, 2011). Although these numbers have relatively high uncertainties, they highlight the scale at which air pollution affects societies. Furthermore, air pollution is projected to become the major cause of premature mortality by 2050 according to the OECD Environmental Outlook to 2050 (OECD, 2012), based on ground level Ozone (O_3) and particulate matter (PM) alone, with 4.3 million premature deaths. These scenarios predict more than a doubling of premature deaths due to particulate matter with respect to 2010.

Air pollution is expected to worsen due to development (Hutton, 2011) and other factors like increasing world population, urbanisation, and ageing of population (long term exposure). While the idea that development could lead to poorer air quality is perhaps intuitive, climate change is expected to further exacerbate air pollution burdens, for example by leading to more stagnant air days (Horton et al., 2014). The need to modify anthropogenic emissions together with a changing climate poses a complex and major challenge. Therefore, socio-economic impact of air pollution on human societies has become an area of intense investigation. A better understanding of the atmospheric processes and the interactions of climate change and air quality measures is mandatory. This is particularly important because, if air quality and climate are considered together, the reduction of air pollution and climate change mitigation can be achieved hand in hand. Identifying win-win scenarios that reduce trade-offs is a key challenge that must be considered as part of science driven policy changes. For an overview of air pollution and climate change the interested reader is referred e.g. to a recent review by von Schneidemesser et al. (2015).

Health impacts of air quality and their cost assessment are commonly calculated using an Impact Pathway Approach (IPA). This includes assessments of emissions, dispersion and atmospheric chemistry of pollutants, impact of population exposure through use of pollutant specific exposure response functions (ERF), population concentration and finally translation into monetary costs.

European research efforts are being carried out within the MACC[2] (Monitoring Atmospheric Composition & Climate) project series, which started in 2005. The outcome of this work has been to establish a European capacity for Earth Observation, known as Copernicus. In MACC, key pollutant concentrations are computed at global and European scales by employing chemically-driven advanced transport models. This offers a unique combination of modelling efforts with observations, because it assimilates Earth Observation data, an ensemble of

[1] EU-28 plus parts of Russia, Ukraine, Belarus, Turkey, etc. (DEHM domain 2, see Brandt et al., 2013, and references therein).

[2] Monitoring atmospheric composition and climate (MACC), www.gmes-atmosphere.eu

chemical transport models and state of the art weather forecasting from the European Centre for Medium-range Weather Forecast (ECMWF[3]).

Combining the results from the MACC model ensemble with a novel integrated assessment model for calculating the health impacts and damage costs of air pollution at different physical scales will yield information at high temporal and spatial resolution. A multidisciplinary approach is needed, bringing together leading experts from natural sciences and socio-economic fields. These calculations are complementary to other, previous and ongoing efforts to assess health impact projections. It benefits the European community by contributing a novel approach to assess air quality at the local and regional levels, explores new pathways for exploiting earth observational data, and benefits to long running EU commitments.

2. Impact pathway analysis

A standard methodology to calculate the economic impact of pollutants is the Impact Pathway Approach (IPA). It was developed in the ExternE project series (ExternE, 2006), which ran from 1991 to 2008, and included more than 50 research teams from 20 countries. ExternE has become a well-recognised source for methods and results of externalities estimation (i.e., the cost that affects society but is not accounted for during production).

The IPA consists of several steps which are described below for the example of atmospheric pollution (ExternE, 2006 and Fig. 1). The depicted IPA only takes into account effects based on inhalation of pollutants. This is of course not sufficient for e.g. persistent organic pollutants or toxic metals, which are deposited and also impact human health via ingestion. More complex pathways have been developed in the framework of ExternE (e.g., Uniform World Model, UWM, Spadaro & Rabl, 2004), however, in this working paper the term atmospheric pollutants/air quality only refers to compounds which impact via inhalation (e.g. O_3, NO_X, SO_2, VOC, PM).

A. Activity to be assessed and the background scenario where the activity is embedded. Concentrations of pollutants can be defined by their emission, dispersion, and atmospheric chemistry.

   I. Emission: specification of the relevant technologies and pollutants, e.g. kg of oxides of nitrogen (NO_X) emitted per GWh by a power plant at a specific site.

   II. Dispersion: calculation of increased pollutant concentrations in all affected regions, e.g. incremental concentration of ozone, using models of atmospheric dispersion and chemistry for ozone (O_3) formation due to NO_X.

   The use of chemical transport models (CTMs) to estimate impacts of air pollution on human health is well-established, and can yield estimations when air quality measurements or networks are sparse or non-existent (Liu et al., 2009; Anenberg et al., 2012; Silva et al., 2013). Furthermore, they can be used to study long range transport, taking into account non-linear effects of atmospheric chemistry. However, they are usually applied for a reduced time frame only (e.g., a certain year), due to the computational costs involved.

[3] European Centre for Medium-Range Weather Forecasts (ECMWF), www.ecwmf.int

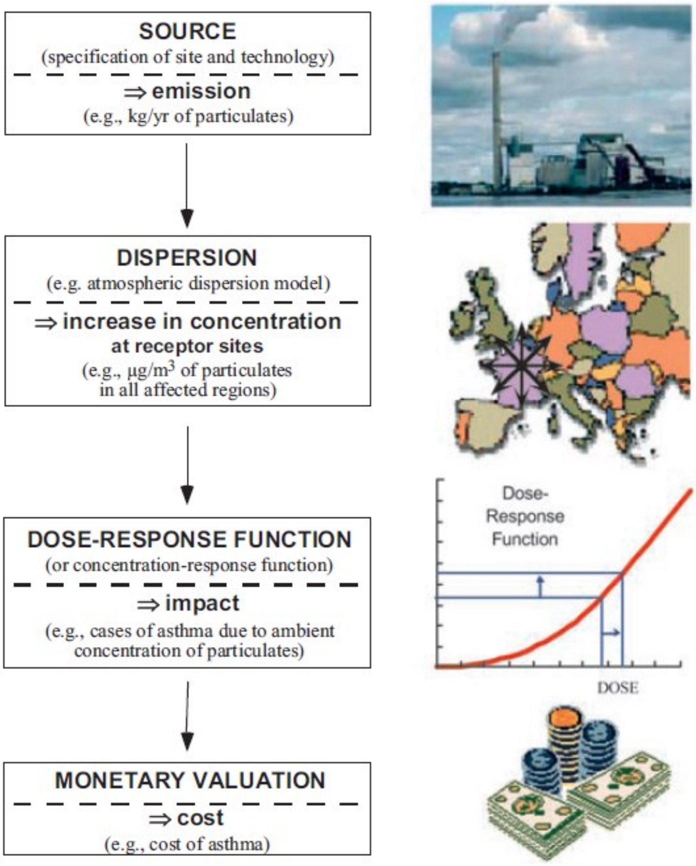

Figure 1: Impact Pathway Analysis for the example of air pollution. Please note that throughout the text dose-, concentration-, and exposure-response functions are used synonymously. From ExternE (2006).

B. Estimation of the additional impacts or effects of the activity (in physical units). In general, the impacts allocated to the activity are the difference between the impacts of the scenarios with and without the activity.

   I. Impact: calculation of the cumulated exposure from the increased concentration, followed by calculation of impacts (damage in physical units) from this exposure using an exposure-response function, e.g. exacerbation of asthma due to this increase in O_3.

C. Monetisation of the impacts, leading to external costs. Damage costs of health impacts are estimated from the possible health impacts, ranging from mortality to days with symptoms of ill health.

   I. Cost: valuation of these impacts in monetary terms, e.g. multiplication by the monetary value of a case of asthma.

   Mortality is commonly valued employing two methods. The value of statistical life (VSL) is based on the number of deaths associated with the pollution. Value of a life year (VOLY) is a method assessing the loss of life expectancy (expressed as years of life lost, or YOLLs). The choice of which of approach is to be employed depends on how we choose to value mortality. See e.g. the best available techniques reference document on economics and cross media effects (EIPPCB, 2006) or results of the Aphekom project.[4]

D. Assessment of uncertainties, sensitivity analyses.

System models like RAINS/GAINS (Aman et al., 2011) are based on bottom-up emission inventories, and apply standardised source-receptor relationships.[5] In-situ measurements may be assimilated, but require additional computations to address diffusion on a wider scale. EcoSenseWeb[6] has been developed in the framework of ExternE by the EU projects "New Energy Externalities Development for Sustainability" (NEEDS[7]) and "Cost Assessment for Sustainable Energy Systems" (CASES[8]). It is an integrated atmospheric dispersion and assessment model. The IPA is used to analyse the impact of an individual point sources in Europe, although multi- emission sources are feasible for certain regions. It can therefore yield valuable information for the studied emitter only.

3. Major air pollutants and their effects on human health and environment

In general, air pollution aggravates morbidity and leads to premature mortality (see Table 1, ExternE, 2006). One can distinguish between classical air pollutants (PM, NO_X, SO_2, O_3) which are inhaled and other pollutants which impact human health via ingestion. A selection of major air pollutants is briefly presented with a focus on classical air pollutants. For a thorough description the interested reader is referred to e.g. WHO (2006) together with its recent updates REVIHAAP (2013) and HRAPIE (2013).

Table 1: Air pollutants and their effects on health. Source: ExternE (2006)

Primary Pollutants	Secondary Pollutants	Impacts
Particles (PM_{10}, $PM_{2.5}$, black smoke)		• Mortality. • Cardio-pulmonary morbidity (cerebrovascular hospital admissions, congestive heart failure, chronic bronchitis, chronic cough in children, lower respiratory symptoms, cough in asthmatics).
SO_2		• Mortality. • Cardio-pulmonary morbidity (hospitalization, consultation of doctor, asthma, sick leave, restricted activity).
SO_2	sulphates	• Like particles?
NO_X		• Morbidity?
NO_X	nitrates	• Like particles?
NO_X + VOC	ozone	• Mortality. • Morbidity (respiratory hospital admissions, restricted activity days, asthma attacks, symptom days).

[4] Aphekom (Improving Knowledge and Communication for Decision Making on Air Pollution and Health in Europe), www.aphekom.org

[5] Source-receptor relationship: How a certain pollutant source of given strength in one location affects the air quality at the receptor location. Pollutants at source and receptor may differ due to chemical conversion.

[6] EcoSenseWeb, http://ecosenseweb.ier.uni-stuttgart.de/, accessed 10.05.2015.

[7] NEEDS, New Energy Externalities Development for Sustainability, http://www.needs-project.org/, accessed 10.05.2015.

[8] CASES, Cost Assessment for Sustainable Energy Systems, http://www.feem-project.net/cases/index.php, accessed 10.05.2015.

CO	• Mortality (congestive heart failure). • Morbidity (cardio-vascular).
PAH (diesel soot, benzene, 1,3-butadiene, dioxins)	• Cancers.
As, Cd, Cr-VI, Ni	• Cancers. • Other morbidity.
Hg, Pb	• Mortality. • Morbidity (neurotoxic).

- **Particulate matter (PM)**

  Particulate matter usually refers to solid and liquid particles suspended in the atmosphere. It is measured in mass concentrations and usually grouped into PM_{10}, $PM_{2.5}$ and PM_1 where the indices describe the maximum aerodynamic diameter in μm of particles included. Depending on the formation pathways of PM, it is further distinguished between primary and secondary PM. Whereas primary PM are directly emitted at the source, secondary particles are a product of chemical reactions in the atmosphere. Precursor gases of secondary PM are mainly SO_2, NO_X, NH_3 and some VOCs.

  PM is one of the most important pollutants with respect to adverse human health impact. PM exposure aggravates cardiovascular disease, or can cause lung cancer (Pope III et al., 2002). Furthermore, PM has been linked to atherosclerosis, adverse birth outcomes and childhood respiratory disease, and indications exists that link long-term $PM_{2.5}$ exposure to neurodevelopment and cognitive function, as well as other chronic disease conditions, such as diabetes (REVIHAAP, 2013).

- **Sulphur dioxide (SO_2)**

  The major contribution to atmospheric SO_2 results from anthropogenic fossil fuel burning (industrial, power plants, shipping). Other sources of SO_2 include biomass burning, volcanic emissions, and it is a product of reactions of oceanic dimethyl sulphide (Dentener et al., 2006; von Schneidemesser et al., 2015). SO_2 has adverse health effects on the respiratory system. Studies of short-term exposures of SO_2 (10 minutes) showed that changes in pulmonary function and respiratory symptoms may be experienced (WHO, 2006). Long-term exposures (over 24 hours) are not easily quantified. WHO guideline values for SO_2 were linked to PM prior to 1987, because SO_2 contributes to its formation. However, some studies documented independent effects of PM and SO_2, e.g. Hedley et al. (2002). SO_2 contributes to acidification, with potentially significant impacts including adverse effects on aquatic ecosystems in rivers and lakes, and damage to forests.

- **Nitrogen oxides (NO_X = NO and NO_2)**

  Nitrogen oxides (NO_X = NO and NO_2) are mainly emitted from fuel combustion; other sources include biomass burnings, soils and lightning. NO_X plays a major role in the atmospheric chemistry because of its connection to O_3 as both a precursor, and at high concentrations as a nitration sink (Seinfield & Pandis, 2006). NO_2 causes adverse effects on health: high concentrations can cause airway inflammation, reduced lung function, asthma. Furthermore, NO_X is a key species in reaction cycles leading to particle formation with respective adverse health effects (WHO, 2006). NO_2 also contributes to acidification and eutrophication.

- **Ammonia (NH_3)**

  The biggest source of NH_3 emissions in Europe is the agricultural sector, which contributes about 94% of total emissions. Further anthropogenic sources are various industrial processes that release smaller amounts of NH_3. Ammonia contributes to both eutrophication and acidification. Furthermore, it is an important species in the production of secondary particulate matter. NH_3 can undergo reactions to form ammonium sulphate and ammonium nitrate, depending of the amount of sulfuric and nitric acid present. Both sulfuric and nitric acid arise from the oxidation of SO_2 and NO_2, respectively.

- **Volatile organic compounds (VOCs)**

  VOCs are commonly distinguished between methane (CH_4) and non-methane volatile organic compounds (NMVOCs). CH_4 influences atmospheric chemistry via its reaction with the hydroxyl radical (OH) and subsequent reactions affecting atmospheric O_3 formation. Furthermore, CH_4 is the second most important greenhouse gas after CO_2 accounting for about 20% of total CO_2-equivalent greenhouse gas emissions[9] in 2010 (IPCC, 2014).

  NMVOCs constitute important ground-level O_3 precursors. Anthropogenic NMVOCs are emitted from a large number of sources including industry, paint application, road transport, dry-cleaning and other solvent uses. Health impacts of NMVOCs result from their contribution to O_3 production and also from the direct toxicity of certain NMVOC species. Benzene (C_6H_6) and 1,3- butadiene, formaldehyde, and styrene are directly hazardous to human health because they are potentially mutagenic or carcinogenic.

- **Ozone (O_3)**

  Ozone is one of the most important atmospheric trace gases with very different impacts on human health, and the environment depending on its spatial distribution in the atmosphere. The stratospheric O_3 layer filters harmful highly energetic ultra-violet solar radiation. Tropospheric ozone, on the other hand, can have adverse effects. It is a product of photo-chemical reactions involving nitrogen oxides (NO_X), carbon monoxide (CO), methane (CH_4) and non-methane volatile organic compounds (NMVOCs) (e.g., Seinfield & Pandis, 2006). If present at elevated levels, it can cause decreased pulmonary functions and increase in asthma and other respiratory diseases, and increase in premature mortality (Silva et al., 2013). Furthermore, it affects vegetation because it is a phytotoxic stress factor, and acts as a greenhouse gas in the lower atmosphere.

- **Carbon monoxide and dioxide (CO and CO_2)**

  Emissions of CO and CO_2 arise from diverse sources, and most notably from combustion of fossil fuels and biomass (IPCC, 2014). Part of these emissions equilibrates among a number of natural carbon sinks, but anthropogenic excesses remain in the atmosphere (with average concentrations in the Northern hemisphere around 400 ppm for CO_2 and 0.20 ppm for CO), causing global warming, ocean acidification, and significant changes in atmospheric composition and chemistry (Faria et al., 2013). Thus, even though neither CO nor CO_2 are directly harmful to human health at ambient concentrations, they cause severe damage to health through their impacts on climate and environment.

[9] Greenhouse gas emissions are calculated in gigatons of CO_2-equivalent per year ($GtCO_2$-eq/yr), based on 100-year Global Warming Potential (GWP100) of respective gas using the most recent GWP100 values from IPCC (2014).

Carbon monoxide is a major sink of tropospheric hydroxyl radicals (OH), and can therefore affect the levels of numerous OH-reactive trace species, including methane, thereby contributing to the production of ozone (Brasseur et al., 1999; Crutzen, 1973; Daniel & Solomon, 1998). At high concentrations (> 30 ppm), CO is highly poisonous, as it binds to haemoglobin and impairs the delivery of oxygen to the vital organs. Such concentration levels are sometimes reached in large urban pollution events, or through heavy tobacco smoking in poorly vented rooms, and leads to symptoms ranging from disorientation, headache, nausea, dizziness and fatigue, high blood pressure and visual disturbance. Chronic exposition to such CO levels increases the risk of cardiovascular and neurological diseases. At very high concentrations (> 600 ppm), CO becomes lethal.

Also carbon dioxide may become lethal at very high concentrations (> 40‰), due to oxygen deprivation (asphyxia). High CO_2 levels (> 2‰) in poorly vented rooms lead to symptoms similar to those listed for high CO concentrations. Owing to its high warming potential, CO_2 still may affect human health at lower concentrations, through the formation of urban CO_2 domes, which stagnate the air column above cities, increasing local temperature, water vapour, ozone, and particulate matter concentrations (Jacobson, 2008, 2010; Spadaro et al., 2013a,b).

The major sectors contributing to the respective emissions were identified in EEA (2007), see Fig. 2. The energy sector and road transport were the main sources of primary and secondary PM. Transport (road and off-road) was also a major source of precursors to O_3 formation. Agriculture plays a significant role in the emission of acidifying and eutrophying substances with respect to ecosystem impact, but contributes less to impact on human health via PM and O_3 .

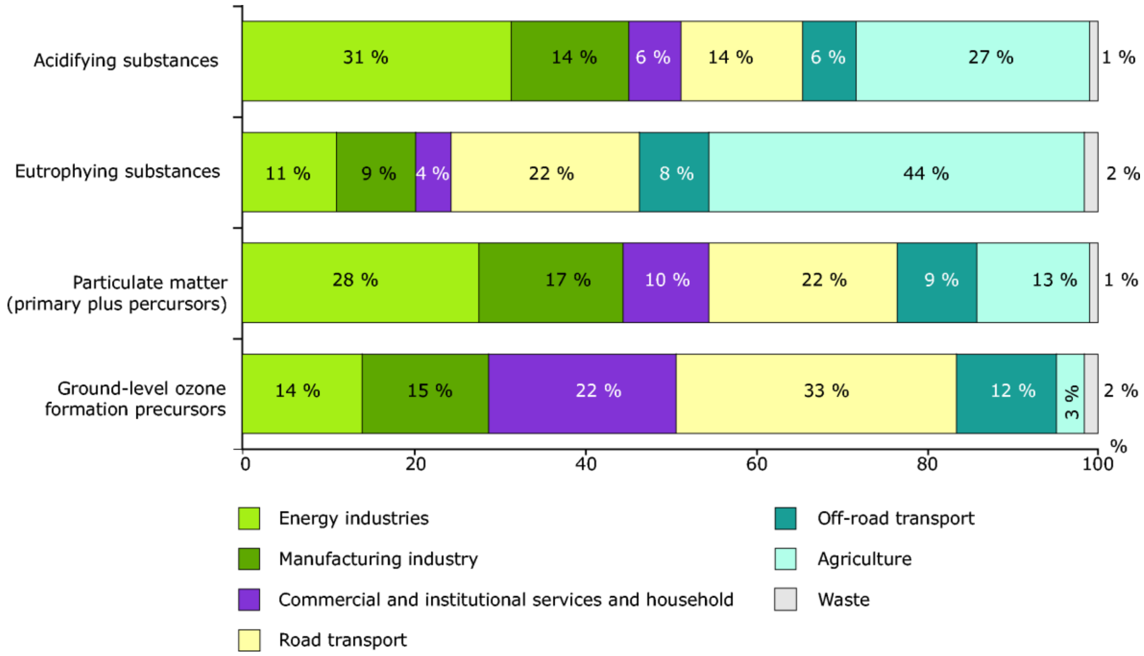

Figure 2: Relative contribution of different sectors to the impact of emissions of air pollutants on ecosystems and human health in Europe (EEA-32 and Croatia), 2004. The first two bars (from top) refer to ecosystem impacts, the third to human health impacts, and the fourth to health and vegetation impacts. Source: EEA (2007).

4. Aggregated damage costs of air pollution for European emissions

The report *Revealing the Costs of Air Pollution* by the European Environment Agency (EEA, 2011) assessed the damage cost of air pollution from industrial facilities in Europe[10] to human health and the environment. The authors used publicly available data of 2009 from the European Pollutant Release and Transfer Register (E-PRTR[11]). Damage costs of air pollutant emissions were quantified in monetary terms based on the IPA with data from ExternE. By employing these methodologies, the study addressed various questions, e.g., to which degree different emissions or activity sectors as well as countries contribute to air pollution damage costs in Europe; how the estimated damage costs are distributed among the facilities; and which facilities cause the highest estimated damage cost according to the E-PRTR.

The E-PRTR data used consisted of emissions to air from 9,655 facilities for the year 2009. In addition to the classical pollutants mentioned previously, also heavy metals (arsenic, cadmium, chromium, lead, mercury and nickel), organic micro-pollutants (benzene, dioxins and furans, and polycyclic aromatic hydrocarbons) were included. Damage costs of health impacts were calculated depending on the emitted pollutant. For NH_3, NO_X, PM, SO_2 and NMVOC mortality was valued using two commonly applied methods, the value of statistical life (VSL) and the value of a life year (VOLY). Heavy metals and organic micro-pollutants on the other hand were valued using VSL only. This is appropriate because exposure leads to a more substantial loss of life expectancy (cancers or other forms of serious ill health). Greenhouse gas emissions were taken into account and estimated for CO_2 to show both, the effect of poor air quality and climate change. Damage costs arising from CO_2 emissions assumed a cost of €33.6 per tonne (insert). This was based on a methodology developed by the UK government for carbon valuation in public policy appraisal. In order to calculate the total damage costs, country specific estimates of damage costs were applied.

The total aggregated emissions to air and resulting damage costs are shown in Fig. 3 for selected pollutants. Note the logarithmic scale on the left panel. Depicted emissions vary approximately by a factor of 1,000 (10 if CO_2 is excluded). The resulting damage costs are depicted on the right panel of Fig. 3. It is immediately visible that the most damaging pollutant is CO_2, followed by SO_2, NO_X, NH_3, PM_{10} and NMVOCs. The impact of different valuation schemes (VOLY, VLS) is also apparent. As a key finding of the study, the cumulative damage costs of emissions in 2009 are estimated in the range of 102–169 bn € (VOLY - VLS). Further assessment included the damage costs generated by the different industrial sectors. The pie chart on the right panel of Fig. 3 shows their relative contribution to the total damage costs. The inner ring depicts results for valuing mortality using VOLY, outer ring employing VLS. The sector of biggest impact was identified to be the power generating sector with 66–112 bn €, followed by production processes with 23–28 bn €. All costs are based on 2005 prices.

If the facilities are ordered according to their damage costs, it becomes apparent that the greatest damage is caused by a small number of facilities. 50% of the total damage results from only 2% of the ca. 10,000 facilities with reported emissions to the atmosphere (Fig. 4). The greatest emitters are located in Germany and Eastern Europe, and belong to the energy sector.

However, care must be taken when interpreting these results based on E-PTRT data alone. The completeness of reported values varies with facility, country and industrial sector. E.g., the agricultural sector is only included to small fraction and more difficult to assess than

[10] 27 EU Member States and Iceland, Liechtenstein, Norway, Serbia and Switzerland.
[11] E-PRTR - The European Pollutant Release and Transfer Register, http://prtr.ec.europa.eu

large power generating facilities. Furthermore, the efficiencies of individual facilities are not registered in the E-PRTR. E.g., a big but efficient facility may be not as harmful to the environment as a number of smaller, less efficient facilities of equivalent production. It is therefore not unambiguously possible produce a ranking of facilities according to their environmental efficiency. Individual CO_2 emissions are used as a proxy for fuel consumption in an attempt to normalize the individual damage costs. In that case, the case Eastern Europe shows an increased number of facilities with greatest damage costs.

Sensitivity of the results to assumptions of input data should also be considered. One example is the range of values obtained by using the different valuation methods. However, the authors state that although the employed methods are likely to be improved, a substantial change in relative importance of individual sectors is unlikely.

The gained insights can be further improved by employing revised impacts of pollutants on human health and damage costs, including further data sets, e.g., efficiency of facilities, and more complete reporting of emissions. However, the results yield relevant information which act as a framework for discussions on pathways to a sustainable, low carbon and resource efficient economy.

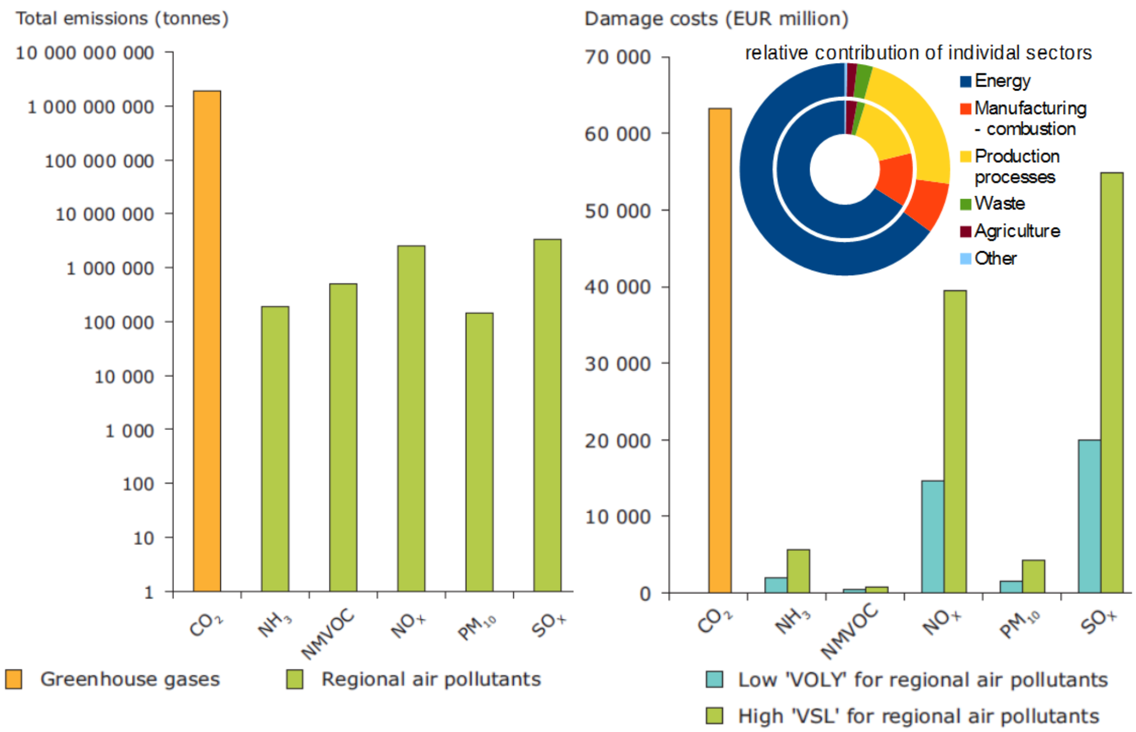

Figure 3. Left: Annual sum of emissions to air in 2009 as given by the E-PRTR. Only selected pollutants are shown. Please note the logarithmic scale of the Y-axis. Right: Annual sum of damage costs in 2009 for selected air pollutants. Lower and upper boundaries of calculations (blue and green bars, respectively) correspond to different valuation of mortality. The plotted pie chart displays the relative contribution of individual sectors using valuation VOLY and VSL for the inner and outer ring, respectively. All costs are based on 2005 prices. Figures adapted from EEA (2011). Heavy metals and organics are not shown because their combined contribution was considered small (< 0.5 bn €) in EEA (2011).

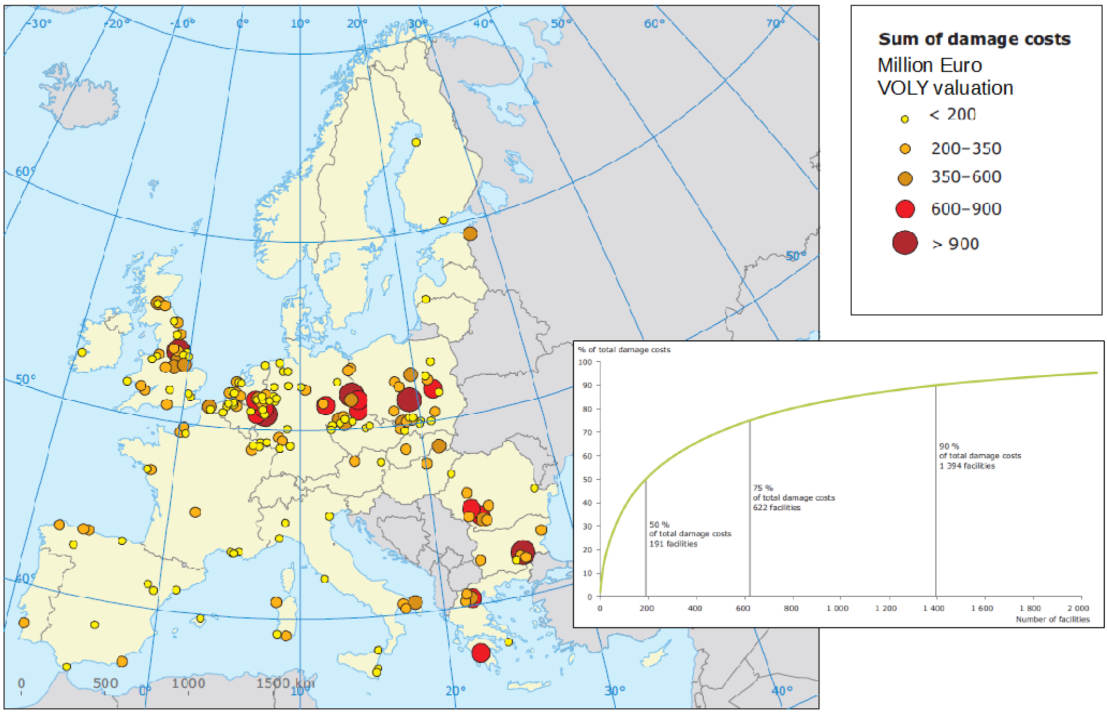

Figure 4: The map shows the 2% of all facilities which contributed 50% to the total estimated damage costs for 2009. The cumulative distribution of all facilities is depicted in the graph at the lower right corner. Source: EEA (2011)

5. Going beyond ExternE

5.1 MACC, Earth observation data products

So far untapped potential for economic cost assessment of air pollution lies in the assimilation of Earth observation products. By employing sets of satellite data, air quality information can be obtained world-wide. Resolution may vary greatly between different satellites, e.g. ~ 30 x 60 km² for Sciamachy in nadir viewing direction, 2002–2012 on Envisat (e.g., Gottwald et al., 2006) and 7 x 7 km² for Tropomi (Veefkind et al., 2012) on the upcoming Sentinel 5 Precursor mission (to be launched in 2016). Greater footprints pose a difficulty to determine small individual point sources, and the surface sensitivity of satellite measurements depends on the observation wavelength. However, Earth observations allow global coverage over longer time scales and include regions for which ground based measurements are not available.

The Monitoring Atmospheric Composition and Climate projects, MACC, including MACC I, II, and the ongoing MACC III, are a long running effort since 2005 in the establishment of a European capacity for Earth Observation, Copernicus, previously known as GMES (Global Monitoring for Environment and Security). It is a major European project involving 36 partners, including the European Centre for Medium-range Weather Forecast, ECMWF, and several national meteorological institutions. Satellite and in situ data are used together to drive an ensemble of chemical transport models (CTMs) for regional and global analysis and forecasting. These are coupled to the ECWMF integrated forecasting system (IFS), which supplies the meteorological boundary conditions. An ensemble of different models is available for critical air pollutants O_3, $PM_{2.5}$, PM_{10}, SO_2, and NO_X on the European and global scale for a spatial resolution of ~ 10 x 10 km² and ~ 140 x 140 km², respectively, and at different time resolutions. A portfolio of data from ground based to satellite measurements is

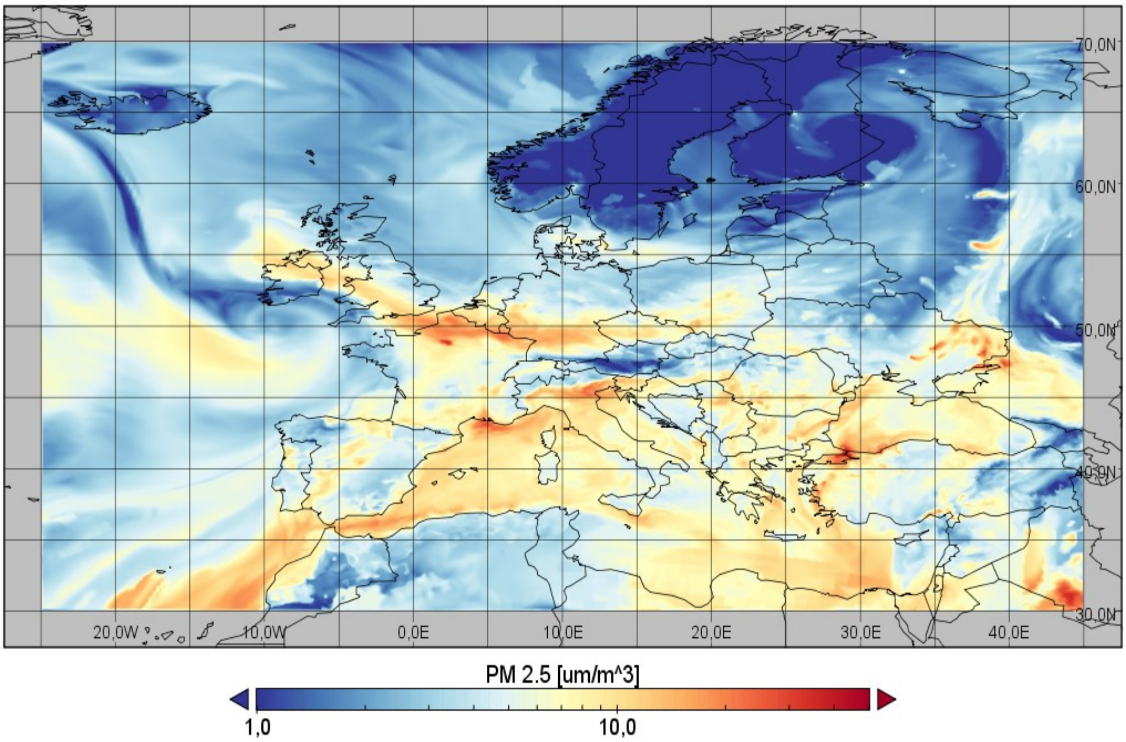

Figure 5: $PM_{2.5}$ surface concentration as modelled by the MACC II ensemble for 08:00h GMT on May 14th, 2015 (MACC, 2015). Please note the logarithmic colour scale, ranging from 1 to 50

assimilated to ensure the high validity of the model runs. For a short introduction the reader is referred to Flemming et al. (2013) and further links on the MACC homepage.[12]

A key advantage is the significant error reduction achieved by using an ensemble of CMTs for Europe in comparison to the individual models. Furthermore, source-receptor relationship calculations may be available on request for chosen areas and times. An example is shown in Fig. 5, which depicts surface concentrations of $PM_{2.5}$ as modelled by the MACC II ensemble (MACC, 2015). One has to note that these concentrations do not differentiate between anthropogenic and natural sources.

5.2 Combining modelling efforts based on Earth observation data and health impact assessments

A novel integrated assessment system model can be developed to exploit the untapped wealth of information in the MACC data products. It will provide a derivation of health impacts and economic valuation using the concept of an impact pathway analysis to assess the effect of air pollution, see e.g. Rabl et al. (2014). The results may be exploited for observing changes and open new avenues for the study of health impacts of air quality and possible paths for decreasing costs.

By following the IPA, concentration distributions of atmospheric pollutants and aerosols are combined with detailed population data to calculate population exposure, which can in turn be used to calculate adverse health impacts and their societal costs. Only major air pollutants are studied (O_3, $PM_{2.5}$, PM_{10}, SO_2, NO_2, NO_X, CO).

12: www.gmes-atmosphere.eu

However, the air quality model results of the MACC project require additional research efforts before the results can be used in the proposed health impact study. Concentrations are calculated at a coarse spatial grid, especially on the global scale. Air quality data for a grid cell only corresponds to its mean concentration but does not hold any information on the sub-grid concentration differences. Furthermore, care must be taken that the data are prepared at the necessary time intervals of the respective health impact metric, which are usually annual mean values.

The efforts to up-scale MACC concentration fields need to be connected to other input data. E.g., it is necessary to take into account emissions of localized sources and dispersion. A way forward is to use integrating emission data bases, for Europe e.g. Centre on Emission Inventories and Projections (CEIP[13]), and combine these with meteorological data. This can be achieved using an approach as in the Uniform World Model (Rabl et al., 2014) or as outlined recently in Kiesewetter et al. (2014). Furthermore, the air quality data needs to interlink with population data to derive population exposure. The population distribution may strongly correlate with air pollutant concentrations (rural vs. urban areas), which opens possibilities to approximate up-scaled concentration fields. However, this may work only for short lived species and care must be taken with long range transport of pollutants and secondary products.

Exposure response functions may be linear for low exposures, non-linear effects may need to be taken into account for high pollutant concentrations. Economic valuation of the health impact is usually assessed using generalized cost functions which may be applied on regional scales. For instance, the same regional cost is applied in impact analyses in Europe and North America. This however does not capture national variations and cost differences, and valuation represents an additional error source.

Any outcome of such calculations needs to be validated in order to be of any actual use to further studies, policy and decision making. This can be achieved e.g. with regional and local air quality networks, where available, and finer grained data on local health impacts and associated costs in a sub-sample of regions. That acts not only as a validation step, but can also be used for calibration and parametrization, and is an important step in assessing the range of errors contributing to the total error budget.

6. Conclusion

Current economic cost estimates of the health impact of air pollution exceed 765 bn € for the European area alone. Climate change will further exacerbate air pollution burdens; a better understanding of economic impacts of air pollution and the estimation of these effects due to climate change has become an area of intense investigation. Efforts to improve air quality may go hand in hand with reduction of greenhouse gas emissions. Identifying these win-win approaches and avoiding trade-off scenarios is one of the current challenges in climate policy studies.

Providing impact assessments of models driven by earth observation data rather than models relying only on inventories and/or dispersion calculations from point measurements offers an alternative approach to assessing the impact of air quality on society. Furthermore, employing data from model ensembles rather than only a single CTM on a European scale reduces model dependent errors significantly. This research approach is complementary to

[13] CEIP, Centre on Emission Inventories and Projections, http://www.ceip.at/ms/ceip_home1/ceip_home/

current quantification efforts, offers additional knowledge and also acts as a check and balance. Given the estimated impact on societies, even a modest reduction of errors is highly desirable. Although dedicated studies on source/receptor relationships are difficult to implement with the chosen approach, the spatial and time series obtained can act as quasi experiments if linked to known source events. Results may be of assistance in policy and decision making to reduce the burden of health costs on society. In this way, described efforts aid in shaping of long ranging efforts to increase air quality in Europe while coping with climate change and the need to restructure economies from fossil fuel to renewable energy sources.

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References

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., Sandler, R., Schöpp, W., Wagner, F., Winiwarter, W., 2011. Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. *Environmental Modelling & Software,* **26**, 1489–1501. doi:10.1016/j.envsoft.2011.07.012

Anenberg, S.C., Schwartz, J., Shindell, D., Amann, M., Faluvegi, G., Klimont, Z., Janssens-Maenhout, G., Pozzoli, L., Van Dingenen, R., Vignati, E., Emberson, L., Muller, N.Z., West, J.J., Williams, M., Demkine, V., Hicks, W.K., Kuylenstierna, J., Raes, F., Ramanathan, V., 2012. Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls. *Environmental Health Perspectives,* **120**, 831–839. doi:10.1289/ehp.1104301

Brandt, J., Silver, J.D., Christensen, J.H., Andersen, M.S., Bønløkke, J.H., Sigsgaard, T., Geels, C., Gross, A., Hansen, A.B., Hansen, K.M., Hedegaard, G.B., Kaas, E., Frohn, L.M., 2013. Contribution from the ten major emission sectors in Europe and Denmark to the health-cost externalities of air pollution using the EVA model system – an integrated modelling approach. *Atmospheric Chemistry and Physics,* **13**, 7725–7746. doi:10.5194/acp-13-7725-2013

Brasseur, G., Orlando, J., Tyndall, G., 1999. Atmospheric chemistry and global change. In: *Topics in Environmental Chemistry*. Birks, J. (Ed.). Oxford University Press, New York.

Crutzen, P., 1973. Discussion of chemistry of some minor constituents in stratosphere and troposphere. *Pure and Applied Geophysics*, **106**, 1385–1399.

Daniel, J.S., Solomon, S., 1998. On the climate forcing of carbon monoxide. *Journal of Geophysical Research - Atmosphere*, **103**, 13249–13260.

Dentener, F., Kinne, S., Bond, T., Boucher, O., Cofala, J., Generoso, S., Ginoux, P., Gong, S., Hoelzemann, J.J., Ito, A., others, 2006. Emissions of primary aerosol and precursor gases in the years 2000 and 1750 prescribed data-sets for AeroCom. *Atmospheric Chemistry and Physics,* **6**, 4321–4344.

EEA, 2007. *Air pollution in Europe 1990–2004*. European Environment Agency, Copenhagen. ISBN 987-92-9167-964-5, ISSN 1725-9177

EEA, 2011. *Revealing the Costs of Air Pollution from Industrial Facilities in Europe*. European Environment Agency, Copenhagen. ISBN 978-92-9213-236-1, ISSN 1725-2237

EIPPCB, 2006. *Integrated Pollution Prevention and Control Reference Document on Economics and Cross-Media Effects*. European Integrated Pollution Prevention and Control Bureau, Seville. http://eippcb.jrc.ec.europa.eu/reference/BREF/ecm_bref_0706.pdf

ExternE, 2006. *Externalities of Energy Methodology 2005 Update*. *EUR 21951 EN.* Peter Bickel and Rainer Friedrich (Eds.). Office for Official Publications of the European Communities, Luxembourg. ISBN 92-79-00423-9. http://www.externe.info/externe_d7/sites/default/files/methup05a.pdf

Faria, S.H., Spadaro, J.V., Markandya, A., 2013. *Breaking the 400 ppm Barrier: Physical and Social Implications of the Recent CO_2 Rise.* BC3 Policy Briefing 2013/Special Issue-02. Basque Centre for Climate Change (BC3), Bilbao.

Flemming, J., Peuch, V.-H., Engelen, R., Kaiser, J.W., 2013. A European global-to-regional air pollution forecasting system that combines modelling with satellite observations; a novel forecasting system for atmospheric composition operates daily to forecast global air pollution. *EM Magazine*, https://www.gmes-atmosphere.eu/pressroom/

Gottwald, M., Bovesmann, H., Lichtenberg, G., Noel, S., von Bargen, A., Slijkhuis, S., Piters, A., Hoogeveen, R., von Savigny, C., Buchwitz, M., Kokhanovsky, A., Richter, A., Rozanov, A., Holzer-Popp, T., Bramstedt, K., Lambert, J.-C., Skupin, J., Wittrock, F., Schrijver, H., Burrows, J.P., 2006. *SCIAMACHY, Monitoring the Changing Earth's Atmosphere.* DLR, Institut für Methodik der Fernerkundung (IMF). http://atmos.caf.dlr.de/projects/scops/sciamachy_book/sciamachy_book.html

Hedley, A.J., Wong, C.-M., Quoc Thach, T., Ma, S., Lam, T.-H., Anderson, H.R., 2002. Cardiorespiratory and all-cause mortality after restrictions on sulphur content of fuel in Hong Kong: an intervention study. *The Lancet*, **360**, 1646–1652. doi:10.1016/S0140-6736(02)11612-6

Horton, D.E., Skinner, C.B., Singh, D., Diffenbaugh, N.S., 2014. Occurrence and persistence of future atmospheric stagnation events. *Nature Climate Change,* **4**, 698–703. doi:10.1038/nclimate2272

Hutton G., 2011. *Air Pollution - Global Damage Costs of Air Pollution from 1900 to 2050*. Assessment Paper. Copenhagen Consensus on Human Challenges, Lowell, MA

HRAPIE, 2013. *Health risks of air pollution in Europe - Recommendations for concentration-response functions for cost–benefit analysis of particulate matter, ozone and nitrogen dioxide*. World Health Organisation (WHO), Geneva. http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/health-risks-of-air-pollution-in-europe-hrapie-project.-new-emerging-risks-to-health-from-air-pollution-results-from-the-survey-of-experts

IPCC, 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.), IPCC, Geneva.

Jacobson, M.Z., 2008. On the causal link between carbon dioxide and air pollution mortality. *Geophysical Research Letters,* **35**, L03809/1–5. doi:10.1029/2007GL031101

Jacobson, M.Z., 2010. Enhancement of local air pollution by urban CO_2 domes. *Environmental Science and Technology,* **44**, 2497–2502.

Kiesewetter, G., Borken-Kleefeld, J., Schöpp, W., Heyes, C., Thunis, P., Bessagnet, B., Terrenoire, E., Gsella, A., Amann, M., 2014. Modelling NO_2 concentrations at the street level in the GAINS integrated assessment model: projections under current legislation. *Atmospheric Chemistry and Physics*, **14**, 813–829. doi:10.5194/acp-14-813-2014

Liu, J., Mauzerall, D.L., Horowitz, L.W., 2009. Evaluating inter-continental transport of fine aerosols:(2) Global health impact. *Atmospheric Environment,* **43**, 4339–4347. doi:10.1016/j.atmosenv.2009.05.032

MACC, 2015. Monitoring atmospheric composition and climate, MACC II model ensemble, near real time PM2.5 data (macc_pm2.5_conc_fc0 2015-05-14 08:00), http://wdc.dlr.de/data_products/VIEWER/macc/, accessed 16.06.2015

OECD, 2012. *OECD Environmental Outlook to 2050, The Consequences of Inaction*. OECD Publishing, Paris. DOI:10.1787/9789264122246-en

Pope III, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., Thurston, G.D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA,* **287**, 1132-1141. doi:10.1001/jama.287.9.1132

Rabl, A., Spadaro, J.V., Holland, M. 2014. *How Much Is Clean Air Worth? Calculating the Benefits of Pollution Control*. Cambridge University Press, Cambridge.

REVIHAAP, 2013. *Review of evidence on health aspects of air pollution*. World Health Organisation (WHO), Geneva. http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/review-of-evidence-on-health-aspects-of-air-pollution-revihaap-project-final-technical-report

von Schneidemesser, E., Monks, P.S., Allan, J.D., Bruhwiler, L., Forster, P., Fowler, D., Lauer, A., Morgan, W.T., Paasonen, P., Righi, M., Sindelarova, K., Sutton, M.A., 2015. Chemistry and the linkages between air quality and climate change. *Chemical Reviews*, **115**, 3856–3897. doi:10.1021/acs.chemrev.5b00089

Seinfield, J.H., Pandis, S.N. 2006. *Atmospheric Chemistry and Physics - From Air Pollution to Climate Change*, 2. ed.. Wiley, Hoboken, NJ. ISBN: 978-0-471-72018-8

Silva, R.A., West, J.J., Zhang, Y., Anenberg, S.C., Lamarque, J.-F., Shindell, D.T., Collins, W.J., Dalsoren, S., Faluvegi, G., Folberth, G., Horowitz, L.W., Nagashima, T., Naik, V., Rumbold, S., Skeie, R., Sudo, K., Takemura, T., Bergmann, D., Cameron-Smith, P., Cionni, I., Doherty, R.M., Eyring, V., Josse, B., MacKenzie, I.A., Plummer, D., Righi, M., Stevenson, D.S., Strode, S., Szopa, S., Zeng, G., 2013. Global premature mortality due to anthropogenic outdoor air pollution and the contribution of past climate change. *Environmental Research Letters,* **8**, 034005. doi:10.1088/1748-9326/8/3/034005

Spadaro J.V., Rabl A., 2004. Pathway analysis for population-total health impacts of toxic metal emissions. *Risk Analysis*, **24**(5), 1121–1141.

Spadaro, J.V., Faria, S.H., Markandya, A., 2013a. *Alternative Carbon Trajectories for Decarbonizing Urban Transportation*. BC3 Policy Briefing 2013/05. Basque Centre for Climate Change (BC3), Bilbao.

Spadaro, J.V., Faria, S.H., Markandya, A., 2013b. *Decarbonizing Urban Transportation.* BC3 Working Paper 2013-14. Basque Centre for Climate Change (BC3), Bilbao.

Veefkind, J.P., Aben, I., McMullan, K., Förster, H., de Vries, J., Otter, G., Claas, J., Eskes, H.J., de Haan, J.F., Kleipool, Q., van Weele, M., Hasekamp, O., Hoogeveen, R., Landgraf, J., Snel, R., Tol, P., Ingmann, P., Voors, R., Kruizinga, B., Vink, R., Visser, H., Levelt, P.F., 2012. TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications. *Remote Sensing of Environment*, **120**, 70–83. doi:10.1016/j.rse.2011.09.027

WHO, 2006. *Air Quality Guidelines. Global Update 2005. Particulate Matter, Ozone, Nitrogen Dioxide And Sulfur Dioxide.* World Health Organisation (WHO), Geneva. ISBN 92 890 2192 6. http://www.euro.who.int/en/health-topics/environment-and-health/Housing-and-health/publications/pre-2009/air-quality-guidelines.-global-update-2005.-particulate-matter,-ozone,-nitrogen-dioxide-and-sulfur-dioxide

WHO, OECD, 2015. *Economic Cost of the Health Impact of Air Pollution in Europe: Clean Air, Health and Wealth.* WHO Regional Office for Europe, Copenhagen. http://www.euro.who.int/__data/assets/pdf_file/0004/276772/Economic-cost-health-impact-air-pollution-en.pdf

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