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Air quality and climate change: designing new win-win policies for Europe

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Abstract

Anthropogenic activities are responsible for the emission of gaseous and particulate pollutants that modify atmospheric composition. Such changes are, in turn, responsible for the degradation of air quality at the regional/local scale as well as for changes of climate. Air pollution and climate change are two intimately connected environmental issues. However, these two environmental challenges are still viewed as separate issues, which are dealt with by different science communities and within different policy frameworks. Indeed, many mitigation options offer the possibility to both improve air quality and mitigate climate change but, at the same time, mitigation options that may provide benefits to one aspect, are worsening the situation in the other. Therefore, coordinated actions taking into account the air quality-climate linkages are required. These actions need to be based on strong scientific grounds, as recognised by the European Commission that in the past few years has promoted consultation processes among the science community, the policy makers and the relevant stakeholders. Here, the main fields in which such coordinated actions are needed are examined from a policy perspective.

1. Introduction

Climate change and air pollution are both critical environmental issues that humanity is facing. On the one hand, air pollution is globally the second leading risk factor for the global burden of diseases, and the premature deaths due to air pollution are estimated globally as 3.4 millions, 480,000 in Europe only (Lim et al., 2012). On the other hand, the 5th IPCC Assessment Report has clearly stated that "warming of the climate system is unequivocal and, since the 1950s, many of the observed changes are unprecedented over decades to millennia" (IPCC, 2013).

The concept that air pollution and climate change are two environmental issues intimately connected is not new and a publication of the Swedish Environmental Protection Agency in 2009 (Swedish EPA, 2009) had the foretelling title "Air pollution and climate Change: two sides of the same coin?". However, still now, in many areas of both science and policy, these two environmental challenges are viewed as separate issues, which are dealt with by different science communities and different policy departments.

A recent overview paper (von Schneidemesser et al., 2015) summarises the many linkages between air quality and climate change (Fig. 1) and evidences that any policy actions intended to mitigate one of these two issues must necessarily take into account the feedbacks with the other, to avoid that benefits to one sector, will worsen the situation in another.

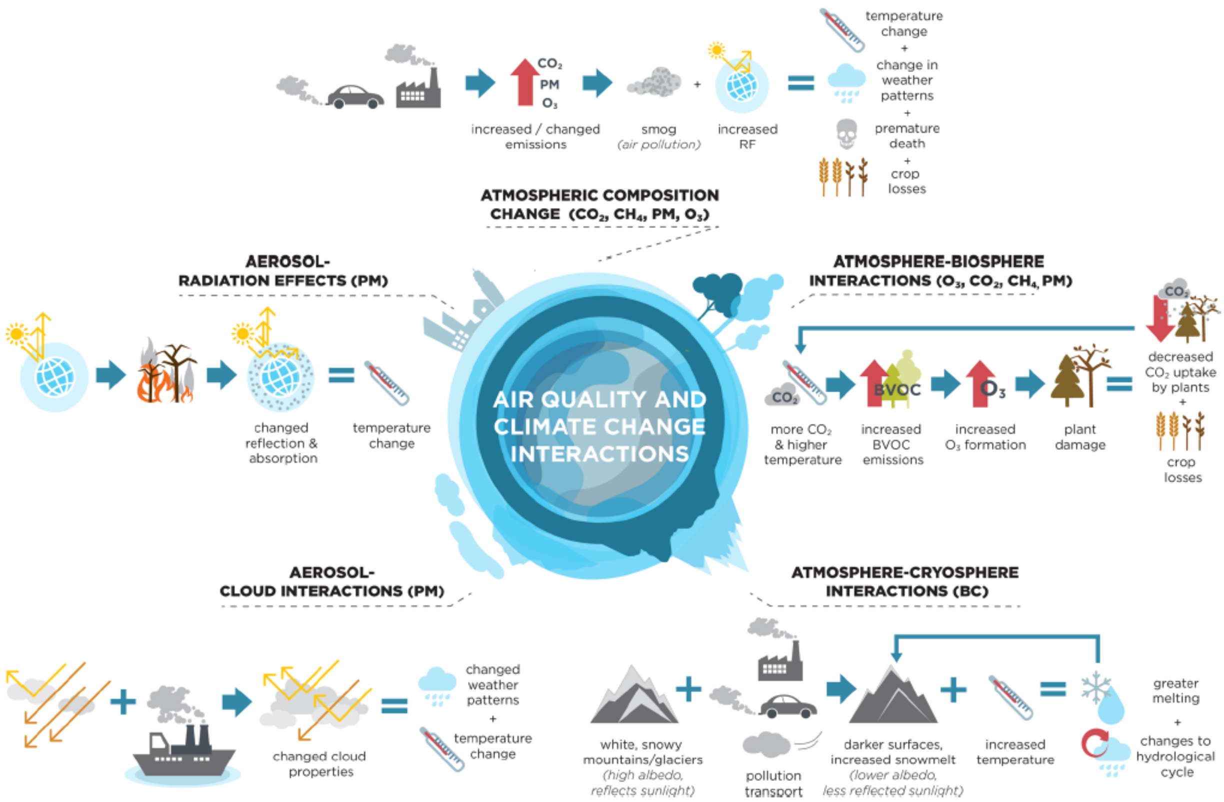

Figure 1 - An overview of the main categories of air quality and climate change interactions. The most relevant components are listed in the brackets following the category (Reprinted with permission from von Schneidemesser et al., 2015).

2. Linkages between air quality and climate change

All anthropogenic activities (e.g. energy production, transportation, industrial processes, agriculture, waste management) are responsible for the emission of gaseous and particulate pollutants that modify atmospheric composition. The atmosphere has, on the other hand, a high self-cleansing capacity, and most pollutants are rapidly removed from the atmosphere by wet and dry deposition or through atmospheric reactions (short-lived compounds, persisting in the atmosphere for times roughly from a few days to a month).

The self-cleansing capacity of the atmosphere is much smaller for other less reactive atmospheric compounds emitted by anthropogenic activities such as carbon dioxide, which remain in the atmosphere for much longer times (long-lived compounds). Carbon dioxide, the main greenhouse gas (GHG) is not considered an atmospheric pollutant since it does not affect human health. On the other hand, also some of the traditional short-lived air pollutants interact with climate. In particular, ozone (Monks et al., 2015) and particulate matter (PM) (Fuzzi et al., 2015) have a strong impact on the Earth radiation balance and thus on climate.

Methane, which has a residence time in the atmosphere of the order of 8 years, lies in an intermediate situation: is a greenhouse gas but also interacts with the atmospheric oxidant cycle and with air pollution in general (Monks et al., 2015).

It is therefore not possible to unambiguously separate anthropogenic emissions in two distinct groups: atmospheric pollutants and climate-forcing species, as evidenced in Table 1. In addition, many of the same sources emit both climate-forcing species and air pollutants.

Table 1 – Residence time, pollutant properties and climate effects of the main atmospheric trace compounds derived from anthropogenic activities.

Compound	Approx. atmospheric residence time	Pollutant effect(s) on health and/or ecosystems	Climate effects
Carbon dioxide (CO_2)	150 years	Ocean acidification, affects photosynthesis	Long-lived climate-forcer
Methane (CH_4)	8 years	Precursor of tropospheric ozone (see below)	Medium-lived climate-forcer
Ozone (O_3)	1 month	Health and vegetation damages	Short-lived climate-forcer
Sulphur dioxide (SO_2)	1 week	Health damages, ecosystem acidification	Precursor of PM sulphate, cooling climate
Nitrogen oxides (NO_X)	1 week	Health damages, precursor of tropospheric ozone, ecosystem acidification, water eutrophication	Precursor of PM nitrate, cooling climate
Ammonia (NH_3)	1 week	Ecosystem acidification, water eutrophication, Health damages	Precursor of PM ammonium, cooling climate
Black carbon (BC)	1 week	Health damages	Absorbs solar radiation, warming climate

The anthropogenic activities influence climate both directly, emitting GHGs and PM, and indirectly emitting short-lived pollutants that are either climate forcing agents themselves or precursors of them. Fig. 2 shows an evaluation of the radiative forcing for the period 1750-2011 of the main trace compounds derived from anthropogenic activities (Myhre et al., 2013).

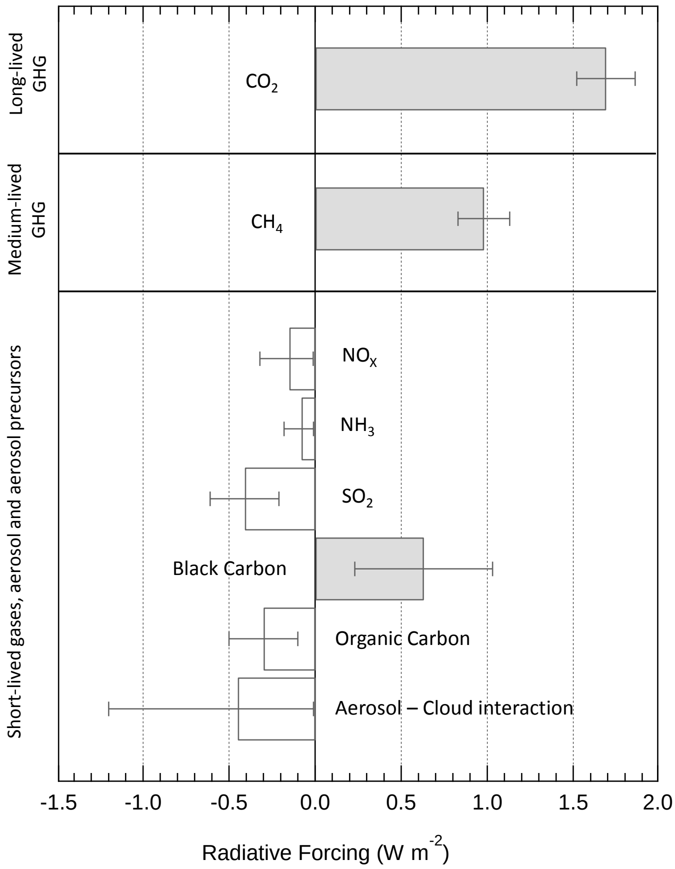

Figure 2 – Radiative forcing from the main gaseous and particulate compounds emitted to the atmosphere by anthropogenic activities from the beginning of the industrial revolution. The grey bars refer to positive forcing (climate warming), the black bars refer to negative forcing (climate cooling). Adapted from (Myhre et al., 2013).

As Figure 2 clearly shows, policy measures to mitigate air quality and climate change must necessarily be integrated, since climate-relevant short-lived compounds such as light-absorbing particulate BC, light-scattering particulate sulphates, nitrates, organics and ozone are at the same time air pollutants affecting human health and climate-forcing (positive and negative) agents.

Many mitigation options offer the possibility to both improve air quality and mitigate climate change. There are, however, also mitigation options that may provide benefits to one aspect, while worsening the situation in the other (win-lose policy options). Coordinated actions that take the air quality-climate change linkages into account therefore provide the most cost-effective strategies.

A pioneering work aimed at proposing integrated measures to mitigate both air quality and climate warming is the Report *Integrated Assessment of Black Carbon and Tropospheric Ozone* (UNEP-WMO, 2011; Shindell et al., 2012). This effort has prompted the start of the high profile political initiative Climate and Clean Air Coalition (CCAC, www.ccacoalition.org), aimed at facilitating faster and more efficient progress toward protecting human health and ecosystems while mitigating near-term climate change.

3. The Policy Framework

At the European level AQ and CC policy frameworks remain separated, with two different Directorates General (DG), the DG Environment and DG Climate Action, dealing with air quality and climate change, respectively. Because of the nature (lifetimes) of the compounds involved for the two issues and because of the different time-horizon, AQ has been dealt through national to local actions, mostly end-of-pipe measures, whereas international (global) agreements are dealing with climate change (UNFCCC).

3.1 Air Quality

Limit values for the main atmospheric pollutants are given in the European Directive on Ambient Air. Currently is in force the Directive 2008/50/EC of the European Parliament and of the Council, adopted in June 2008 and reflecting the DG Environment proposal of September 2005. The 2008 Directive resulted from the merging of the previous Council Directive 96/62/EC on ambient air quality assessment and management with three Daughter Directives on i) PM, ii) Benzene and Carbon Monoxide and iii) ground based ozone and its precursor. The 2008 Directive introduced a key and innovative element, i.e. new AQ objectives for fine PM (PM 2.5) recognised as responsible for significant negative impacts on human health. However, since there is no identifiable threshold below which PM2.5 would not pose a health risk, the Directive aimed at a general reduction of concentrations in the urban background, combining this approach with the introduction of limit values.

With regards to emissions of primary pollutants, these are addressed by the Directive 2001/81/EC of the European Parliament and of the Council on National Emission Ceilings (NECD) for the following atmospheric pollutants: ammonia, nitrogen oxides, non-methane VOCs and sulphur dioxide. The aim of the NECD is to improve the protection of the environment and human health against risks of adverse effects from acidification, soil eutrophication and ground-level ozone. National ceilings in the Directive are similar to those originally set by the Gothenburg Protocol (December 1999) to the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (CLRTAP).

A revision process of the European strategy started in early 2011. Since compliance with existing obligations on PM_{10} and NO_x in the Air Quality Directive (2008/50/EC) is still a problem in many Member States, the Commission have decided not to revise the Directive but rather to focus on a package on measures to reduce the extent of non-compliance. This package, released in December 2013, includes the proposal for a revised NECD (COM (2013) 920 final). The first stage in revising the NECD is to adopt the revised Gothenburg Protocol agreed in May 2012 in the CLRTAP within the UNECE. The revised Protocol includes an emission ceiling for primary PM2.5 and requires reducing source with high proportions of black carbon (BC) in achieving the PM2.5 ceilings. The revised directive also includes emission reduction obligations for methane, precursor of longer-term average ozone concentrations and therefore an important short-lived climate pollutant. The inclusion of climate forcers such as BC, methane and ozone establishes the first legislative link between air quality issues and global warming.

On 28 October, 2015 the European Parliament voted on the Commission's proposal to revise the NECD. The vote did not go as far as the recommendations by the Environment Committee of the Parliament but did strengthen the Commission's proposal, firstly by recommending mandatory emission ceilings in 2025 as well as the original proposal for mandatory ceilings in 2030, and also to require the Commission to produce an impact assessment and a proposal on mercury. The inclusion of methane proposed by the Commission was endorsed but enteric methane emissions from cattle were excluded, a conclusion that will ease pressure on the agricultural sector.

3.2 Climate Change

The United Nations Framework Convention on Climate Change (UNFCCC) is the international treaty (signed by 196 parties) aimed at stabilising GHG atmospheric concentrations at a level that will prevent dangerous human interference with the climate system. During the third Conference of Parties (COP-3) held in Kyoto in 1997, a Protocol was adopted opened on Mar 1998 for signature by parties and entered into force in Feb 2005, after having met the clause of being signed by at least 55 Parties accounting in total for at least 55% of the total carbon dioxide emissions. Within the first phase of the Kyoto Protocol, 37 industrialized countries and the EC have committed to reducing their emissions of the GHGs included in the Kyoto basket (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) by an average of 5 % against 1990 levels over the 5-year period 2008-2012. During the second commitment period (2013 to 2020), Parties committed to reduce GHG emissions by at least 18 percent below 1990 levels. Within the broader global treaties, in 2009 the EU adopted its own climate and energy package to implement the so-called 20-20-20 targets, corresponding to a 20% reduction of GHG emissions compared with 1990 to be achieved by 2020, using a 20 % share of renewables in energy consumption and obtaining an energy improvement by 20 %. In 2014, the EU endorsed new and more ambitious targets for 2030, adopted in 2015 and consisting in a 40% cut in GHG emissions compared to 1990 levels, at least a 27% share of renewable energy consumption and at least 27% energy savings compared with the business-as-usual scenario. Notably, the Kyoto basket does not include important climate forcers, such as ozone and black carbon that are regulated only under the AQ policy frameworks.

4. Short lived climate pollutants

Among atmospheric components that are involved in both air quality and climate change, ozone and PM play a key role, due to their direct adverse effects on human health and ecosystems and their capability to interact with the incoming solar radiation and the infra-red radiation emitted by the earth surface.

4.1 Ozone and methane cycles

Tropospheric ozone is an air pollutant with health and ecosystem impacts (Monks et al., 2015). Ozone remains a policy conundrum, even with substantial precursor reductions over Europe (Fowler et al., 2013), it remains a "persistent menace" (Simpson et al., 2014). Ozone, as distinct from many other GHGs or air pollutants, is not emitted directly into the atmosphere but is a product of tropospheric chemistry. The overall budget of tropospheric ozone is a combination of photochemistry, transport in from the stratosphere and loss at the surface (Monks, 2000). Therefore, ozone's tropospheric concentration and to some extent spatial distribution is related to it precursor levels (NO_X and VOCs) and there distribution. Much of the challenge for controlling ozone is that is an intercontinental transboundary issue in that it, and its precursors, can be transported large distances. Changing background contributions to European ozone levels represents a substantial future challenge to the attainment of ozone limit values (Derwent et al., 2010).

The role of ozone as a climate forcer is often overlooked within the air quality context and vice versa. Changes in tropospheric ozone between 1750 and 2010 have generated a global mean radiative forcing (RF) of +0.40 (90% confidence range: 0.20 to 0.60) W m^{-2} (Myhre et al., 2013). Owing to the aforementioned relationship to the main sources of ozone's precursors (NO_X, CO, and VOCs) having industrial origins the largest changes in RF have been in industrialised regions (Stevenson et al., 2013) somewhat tempered by ozone's other key precursor, CH_4, which is relatively well-mixed owing to its decadal lifetime (Voulgarakis et al., 2013) and ozone's inherent lifetime of a few weeks, which allows transport to reduce zonal heterogeneities

The IPCC AR5 (2013) adopted an approach that demonstrated the direct link between the precursors and the resultant radiative forcing. Interestingly, beyond this there are a number of indirect drivers such as temperature on precursor emissions, ecosystem feedbacks or the role on methane lifetime (von Schneidemesser et al., 2015). For example, the concentration and distribution of O_3 precursors affect atmospheric [OH] and therefore the lifetime of methane (Voulgarakis et al., 2013). These additional climate impacts occur over different timescales, and the net integrated impact on climate of emissions of a particular ozone precursor are complex to diagnose e.g. Fuglestvedt et al. (2010).

There are strong synergies between air quality emissions reduction and achieving climate benefits in that any GHG mitigation scenario tends to drive down air pollutant emissions e.g. (Colette et al., 2012). There is another factor beyond emission reduction that needs to be taken into account, the nature and magnitude of any so-called "climate penalty" (Rasmussen et al., 2013; Wu et al., 2008). Simplistically, an increase in global mean temperature could lead to higher tropospheric ozone, eroding benefits of "costly" emission controls. Many of the questions in respect of climate penalties centre on the treatment of NOx projections that is a vexed issue e.g. (Kim et al., 2015).

Within the air quality and climate change space, a strong case has been made to that the reduction of ozone can offer substantive (one-off) benefit in that if methane, a key ozone precursor, is reduced you get "a two for the price of one" forcer reduction (UNEP/WMO, 2011; Shindell et al., 2012). Shindell et al. (2012) showed that application of 14 measures targeting methane and black carbon emissions could reduce projected global mean warming ~0.5°C by 2050 coupled to required CO_2 reductions, with concomitant health/ecosystem benefits from reduced air pollution (see Figure 3).

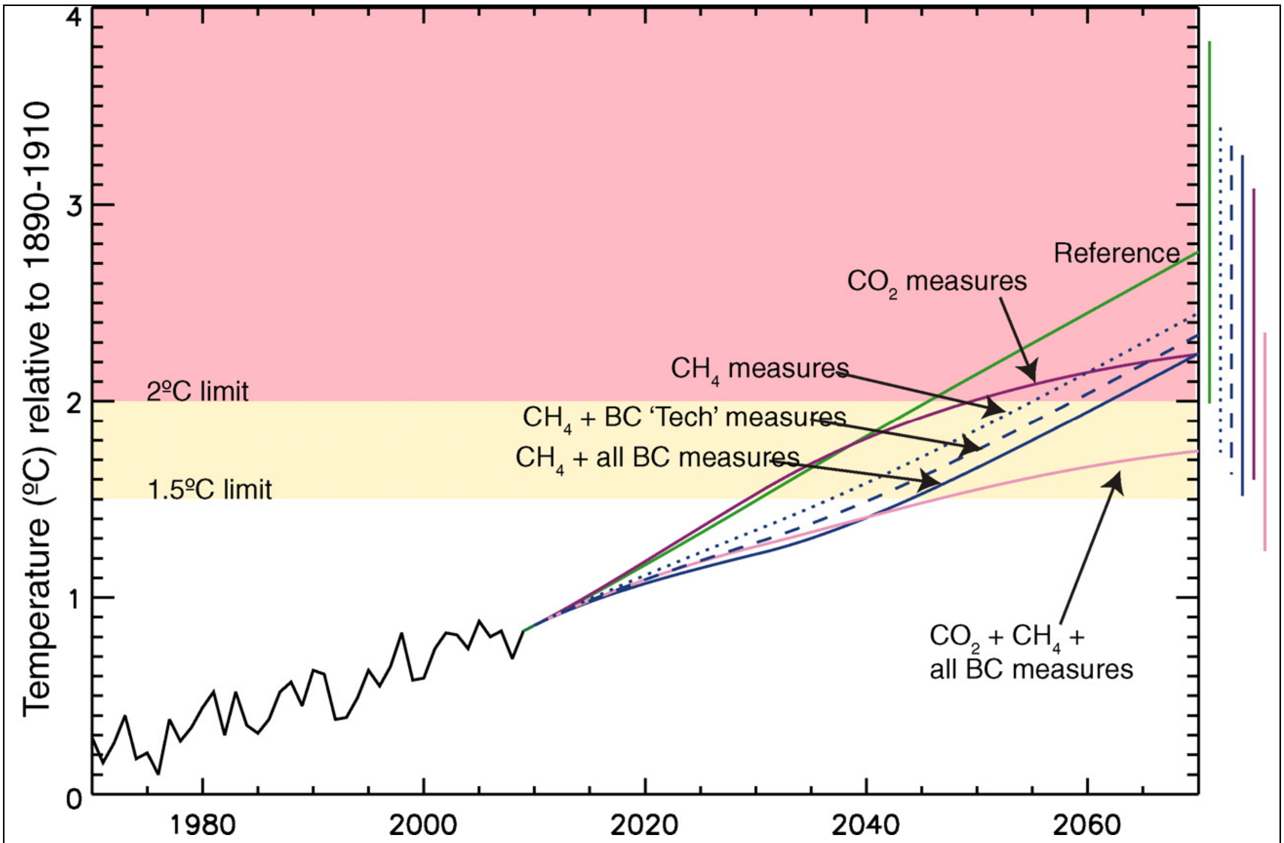

Figure 3 - Observed and projected temperature changes relative to pre-industrial for a range of future precursor reduction scenarios (Shindell et al., 2012).

4.2 *Particulate matter*

Particulate matter is probably the atmospheric component that best exemplifies the air quality-climate change interaction.

On the one hand, PM can induce adverse health effects at low concentrations possibly without a well-defined threshold. Recently, Lelieveld et al. (2015) investigated, using a global atmospheric chemistry model, the link between premature mortality due to PM and seven emission source categories. Their calculated premature deaths per year worldwide, mostly in Asia, is in line with the WHO (2015) estimates. The Lelieveld et al. (2015) results suggest that emissions from residential energy use have the largest impact on premature mortality globally. It is estimated, though, that traffic-related pollution is responsible for a dominant fraction (20%) of the deaths from PM2.5 in the developed world, while it accounts for only 5% on a global scale. This study concludes that without taking appropriate measures, by 2050 the contribution of outdoor air pollution to premature mortality could double.

The mechanisms and different PM types toxicity are a focus of much research. A few epidemiological studies tried to identify specific chemical components in PM and the adverse health outcomes. Evidence was found to the effects of heavy metals on cardiovascular mortality and morbidity (Solenkova et al., 2014) Other studies showed that Cu, K, Zn and Ti in PM2.5 are implicated in different mortality categories, mostly with cardiovascular deaths. Recently, carbonaceous material (soot, black carbon and organic aerosols) is a focus of many studies. Since a dominant fraction of fine-PM mass is composed of organic material, it is more challenging to isolate their health effects through statistical tools typical of epidemiological studies. For example, it was recently shown that SOA and aerosols from biomass burning are major sources for biological effects related to oxidative stress. More common toxicological studies focus on laboratory-generated particles. Humic-like substances, particularly quinones, which are present in SOA, have been shown to lead to oxidative stress, and therefore possibly to health effects.

To better understand and predict the how PM exposure affects public health and in order to devise better tools for improving air quality, several needs have been identified: (i) it is advised to focus on multi-pollutants perspective that should integrate PM sources, their chemical and physical properties and synergistic interactions with gas pollutants, (ii) to establish a fundamental understanding of the underlying mechanisms responsible for PM health effects (including low level, long term exposure), (iii) to improve the methods to obtain exposure estimates using various new sensor technologies, remote sensing (such as the Spartan network), and models, and (iv) promoting an interdisciplinary scientific research approach that integrates atmospheric chemistry, exposure science, new models that predict correctly aerosol composition and number distribution, toxicology, epidemiology and statistics.

On the other hand, PM impacts with climate by scattering and absorbing shortwave and longwave radiation. The climatic effect due to aerosol-radiation interactions (ari) is known as the aerosol direct effect (Isaksen et al., 2009; Haywood and Boucher, 2014) Rapid adjustments to the radiative forcing (RF) by aerosol-radiation interactions are termed by the IPCC 5th assessment report (AR5) RFari, and are also known as “the aerosol direct effect” (Figure 4) (Boucher et al., 2013).

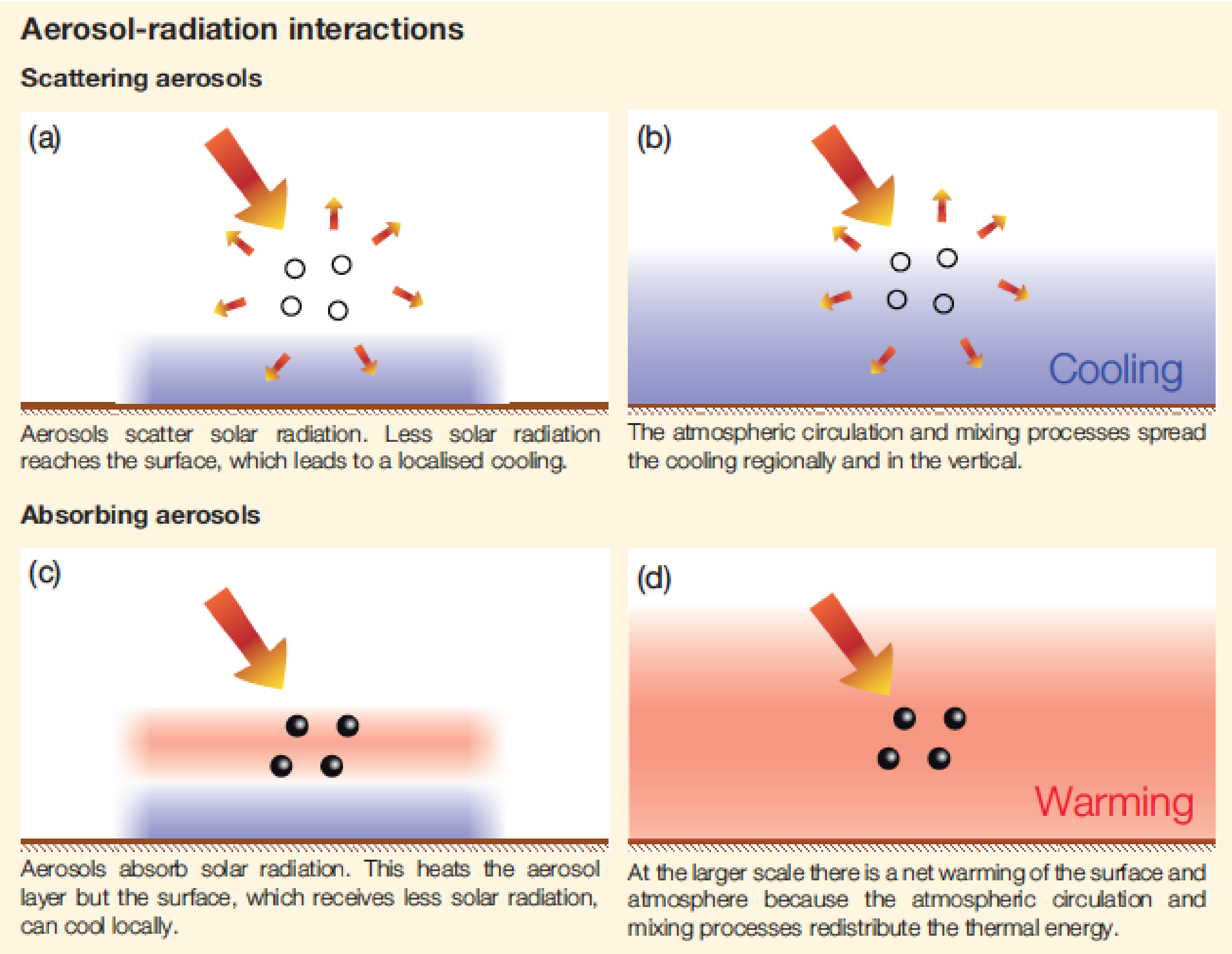

Figure 4 - Overview of interactions between aerosols and solar radiation and their impact on climate. The left panels show the instantaneous radiative effects of aerosols, while the right panels show their overall impact after the climate system has responded to their radiative effects (from Boucher et al., 2013).

Aerosols can also change the properties of clouds by affecting cloud microphysics (Figure 5) (Altaratz et al., 2014). The first aerosol indirect effect, is known as the cloud albedo effect (Lohmann et al. 2005; Mishra, et al., 2014; Davidi, et al., 2012). Aerosol can also affect clouds by “the semi-direct effect” where absorption of radiation be the aerosols modifies the atmospheric temperature profile (Koch et al., 2014). Aerosols may also affect cloud properties through absorption by inclusions of absorbing aerosols between droplets or immersed in the droplets (Jacobson, 2012; Stier et al., 2007). The IPCC AR5 calls these rapid adjustments of the aerosol-cloud interactions RFaci.

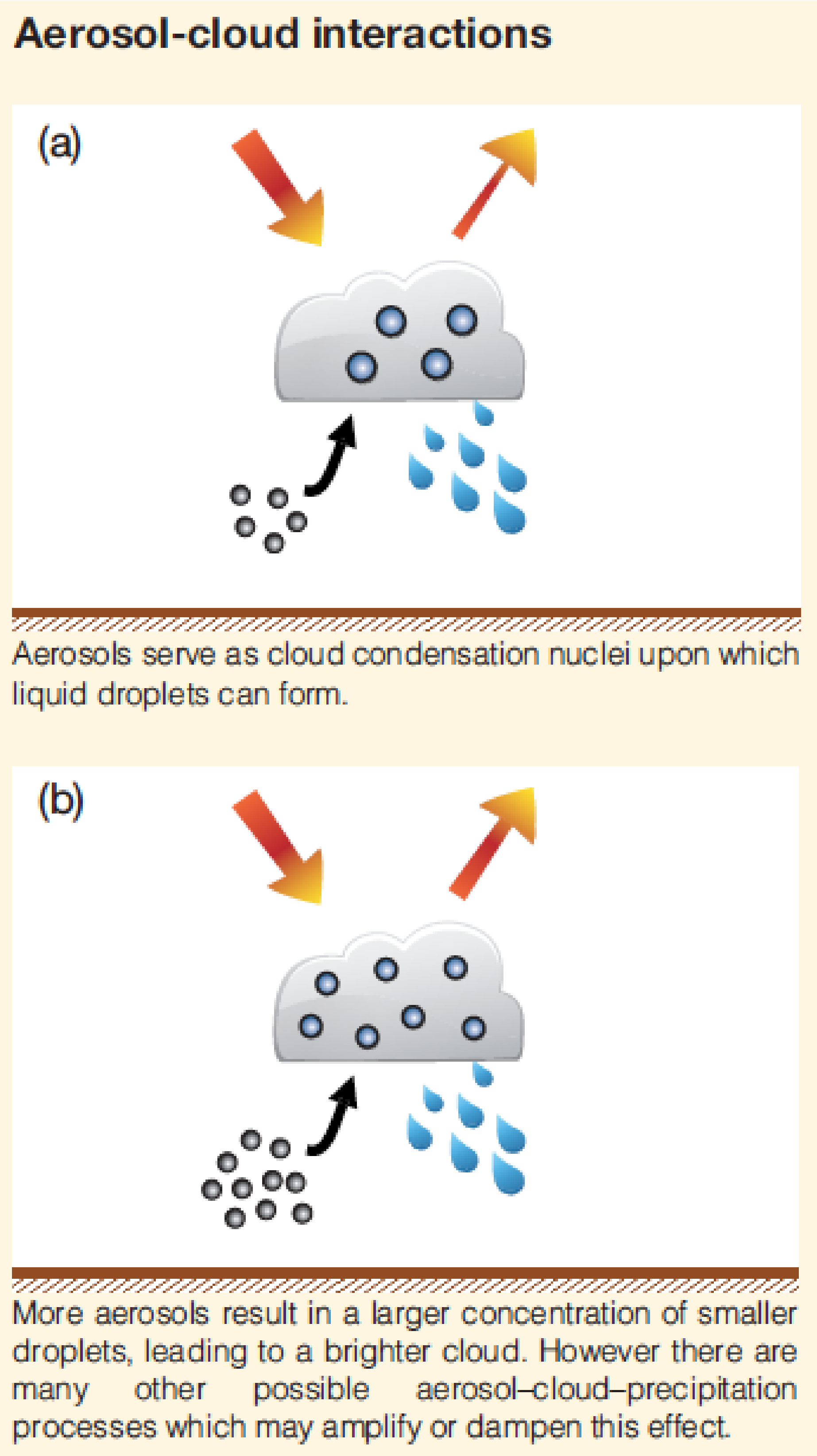

Figure 5 - Overview of aerosol–cloud interactions and their impact on climate. Panels (a) and (b) represent a clean and a polluted low-level cloud, respectively (from Boucher et al., 2013).

Another aerosol effect on climate is through BC and mineral dust particles deposited on snow and ice surfaces and enhance positive radiative forcing and accelerate melting of glaciers and ice caps (Bond et al., 2013; Hansen and Nazarenko, 2004; Ramanathan and Carmichael, 2008).[7] Finally, aerosol deposition to various marine and terrestrial ecosystems, followed by nutrients dissolution may enable various biogeochemical processes that can further affect climate (Mahowald, 2001; Ben-Ami, et al., 2010)

Uncertainty in the magnitude of the aerosol cooling leads to large uncertainties in projections of future climate change (Fiore et al., 2012; Nazarenko, et al., 2015; Shindell, 2015). Removal of this cooling influence due to air pollution abatement policies is underway. In fact, emission control policies are currently being enforced worldwide to improve air quality and to protect human health. The "WHO Air Quality Guidelines" report estimates that reducing annual average PM10 levels from around 70 µg/m3 to 20 µg/m3 could reduce air pollution-related deaths by around 15% in many developing areas. However, even in the developed countries, it is expected that average life expectancy would increase by about 9 months by decreasing PM exposures from human sources.

The air quality policies are therefore expected to enhance future warming (Arnethet al., 2009; Ramanathan and Feng, 2009), and this clearly calls for the integration of air quality and climate policies.

5. Integrated assessment of AQ and CC

The development of Integrated Assessment Modelling (IAM) techniques and their application to the problem of inter-country exchange of pollutants in Europe in the 1980s and 1990s provided a quantitative approach to assess cost effective options for a range of control measures (Altman *et al.*, 1997). Since the early days of IAM development, there has been very extensive development of the underlying sensitivity of ecosystems to pollutant deposition, in large part using Critical Loads methods, to enable effects-based IAM to be applied over regional scales. Such approaches have proved much more widely acceptable to policy makers than arbitrary reduction targets. The IAM methodology provided the policy makers in Europe with an effective numerical tool to develop cost effective controls for Acid Deposition, and has been extended to ground level ozone, eutrophication (by nitrogen compounds) and heavy metals, supporting the development of UNECE protocols and emission ceilings for the countries of Europe (Amann, 2001).

Illustrating, in two dimensions the full range of the multi-dimensional space explored within integrated assessment modelling is difficult, but an essential component of the process includes an assessment of the Benefit-Cost ratio versus the scale of emission reductions achieved (abatement cost curves) to reduce emissions of individual pollutants, as illustrated for NO_2 and NH_3 in Figure 6. In this case the ratio of marginal benefits of emission reductions over costs of mitigation measures for nitrogen measures in Europe illustrate the much larger costs of NO_2 controls, than NH_3 as a consequence of the extensive measures taken for NO_2 to date relative to the largely uncontrolled emissions of NH_3. Applying these relationships along with source-receptor gridded data for each of the pollutants allows the most cost effective pollutant reduction strategies to be identified, and presented to policy makers and their political superiors as part of the negotiation process.

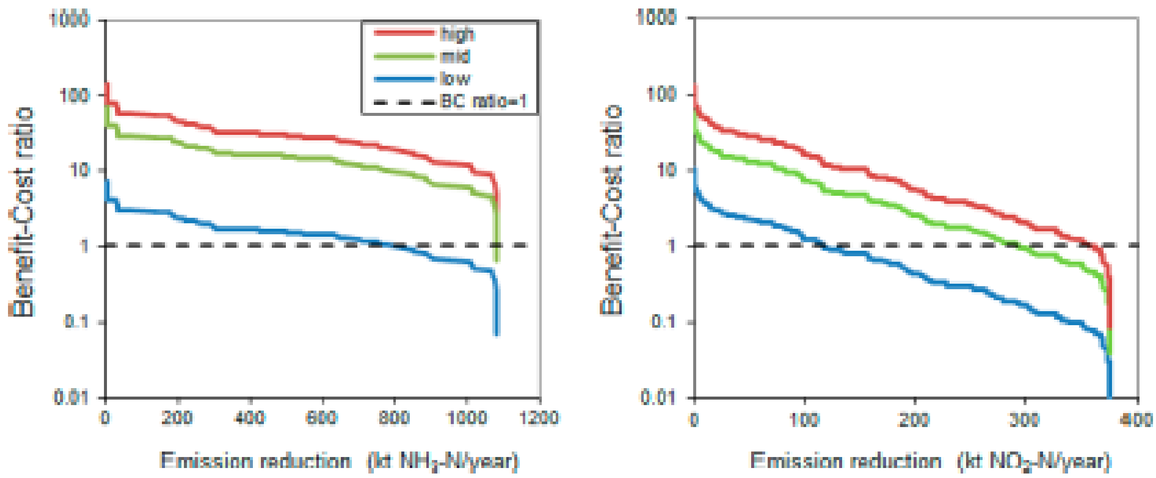

Figure 6**.** Ratio of marginal benefits of emission controls over costs of N mitigation measures for the EU-27 for NO_2 and NH_3 from stationary sources for emission reduction from 2010 beyond expected levels in 2020 by current legislation (adapted from van Grinsven *et al.*, 2013).

In integrated assessment modelling activities, the focus has shifted from a predominantly air pollution effects driven approach in the early stages (e.g. regarding the assessment of policy options to reduce sulphur dioxide emissions in order to combat acidification, towards identifying and quantifying the co-benefits (as well as potential unintended consequences) of combined air pollution and climate change mitigation strategies. Initially, IAMs addressing single pollutant issues typically utilised abatement cost curves for individual pollutants. However, with increasing understanding of the complexity of multi-pollutant multi-effect assessments, measure-based approaches accounting for emissions of air pollutants and greenhouse gases emerged (Reis *et al.*, 2005).

A comprehensive integrated assessment of both air quality and climate change is vital to avoid potential trade-offs (Zusman *et al.*, 2013), for instance where increased utilisation of biomass for residential heating may be effective in reducing the carbon footprint, but in turn contributes to local emissions of PM and thus adverse health effects in residential areas. In a similar fashion, the promotion of diesel vehicles through tax subsidies may have delivered moderate reductions in CO_2 emissions, at the cost of increased emissions of NO_2 and PM in urban areas and premature mortality for many urban dwellers.

Current IAMs focus on the assessment of mitigation options, their associated costs in relation to the effectiveness of achieving reduction targets (Tollefsen et al., 2009), respectively compared to benefits (often as avoided damage costs) realised. Near-term climate change and short-lived climate forcers are mainly investigated (Anenberg *et al.*, 2012; Stohl et al., 2015) due to their explicit links to public health effects, however, the longer term effects of methane and CO_2 continue to be of relevance (Rogelj *et al.*, 2014). A specific challenge emerges from the need to quantitatively assess and compare the benefits from air pollution control and climate change mitigation in a common framework, partly due to differences in spatial and temporal scales, but as well due to the different economic actors bearing mitigation costs and realising benefits. These quantitative assessments are based on a range of approaches to translate benefits into monetary values to make them directly comparable to mitigation (or damage) costs, or other sustainability objectives (Urge-Vorsatz et al., 2014; Schucht et la., 2015; von Stechow et al., 2015).

A crucial aspect of evidence presented by IAMs is that due to the complexity of the challenge to mitigate multiple effects with clear spatial and temporal patterns, communication of results requires a robust science-policy interface (Reis *et al.*, 2012). While at an early stage strategies to reduce SO_2 emissions could be related comparatively easily to improvements in acid deposition and thus benefits in improved forest health on a European scale, presenting today's challenges and the costs and benefits of different options are less straightforward. In the case of short-term vs. long-term climate forcing and their relationship to air quality, some pollutants have a marked contribution to both (e.g. black carbon), whereas others predominantly contribute to one aspect only. In a similar way, challenges differ with regard to time scales (air quality effects are immediate and short-term, while CO_2 or methane have long-term implications) and the type of effects (e.g. human health effects and warming of black carbon vs. the health, ecosystem and crop impacts of reactive nitrogen with potential (small) net cooling effect.

Several European research projects have addressed the complex challenges faced by integrated assessment modelling approaches in recent years: The INTARESE Integrated Project focused on investigating environmental health aspects not as stand-alone issues, but as a consequence of interdependent decisions and events which affect human health in many different ways. In addition, the interactions between pollutants, sources and mitigation options was taken into account. In parallel, the HEIMTSA Integrated Project had the aim to develop a new methodology for evaluating the effects of policy scenarios and quantify both environmental and health impacts. As a key output of both projects, an on-line *Integrated Environmental Health Impact Assessment System* (IEHIAS[1]) has been developed. TRANSPHORM specifically investigated integrated methodologies for assessing particulate matter pollution from transport activities and related health impacts, while the SEFIRA Coordination Action focused on the socio-economic implications of responding to air pollution policies. Most recently, the Appraisal project aimed at a comparative assessment of various methodologies used within European Member States for the integrated assessment of air pollution control strategies. While publications from these research projects are now emerging, their legacy can be seen in bridging existing discipline and domain gaps, integrating researchers and expertise from environmental and health sciences, air pollution and climate change, social and natural sciences and policy.

Finally, the mid- to long-term impacts of emission control strategies require IAM to be conducted over longer time scales, as for instance gradual reduction of NO_2 emissions in urban areas may lead to increases in ground level ozone in hence increases in population exposure for some time, until precursor emissions have been reduced beyond a certain level. To account for this, as well as the long-term aspects of climate change (e.g. Remais et al., 2014), IAMs need to incorporate pathways towards air quality and climate change objectives as much as modelling the ultimate objectives robustly. While the development of IAM methodologies has had its core in Europe, the relevance of taking into account the direct effects and co-benefits of integrated air pollution and climate change mitigation strategies are highly relevant for other world regions (e.g. Dong et al., 2015; Matus et al., 2008; Li et al., 2011; Liu et al., 2013; Mittal et al., 2015)

6. Policy horizon

Air quality policy in Europe is at an interesting stage. The European Commission's Clean Air package, published in December 2013 is currently setting the framework for policy actions but there are further developments that are also likely to have an influence on policy in the coming decade. These developments concern emissions – with some relevance to air quality and climate impacts, ambient air quality and the health impacts of air pollution, and these will be addressed in turn.

The Clean Air package contained a proposal to revise the National Emissions Ceilings Directive (NECD) which went beyond the revised UNECE CLRTAP Gothenburg Protocol in some important areas concerning the co-benefits for air quality and climate change. The emission ceilings proposed by the Commission extend the time horizon beyond the 2020 date set in the Gothenburg Protocol to 2025 and 2030, and added two new pollutants. Following the lead of the Gothenburg Protocol the proposal set emission ceilings for primary emissions of $PM_{2.5}$, with a requirement similar to that in the Gothenburg Protocol, which in achieving these ceilings MSs should give priority to reducing emissions from sources with relatively high proportions of black carbon. The other pollutant included in the proposal was methane, an important source of global tropospheric ozone as well as a powerful greenhouse gas in its own rite. The proposal also tightened the overall emission reductions from the EU Member States, with proposed reductions of 81%, 69% and 51% for SO_2, NO_x and $PM_{2.5}$ respectively, relative to a 2005 base, but only a 27% reduction for ammonia.

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[1] http://www.integrated-assessment.eu/

This highlights a major challenge for future European air quality policy in that ammonia emissions, and those of other pollutants such as methane, from agriculture have not been reduced by anything like the same amount as emissions from other industrial sectors. Ammonia reacts to form important components of $PM_{2.5}$ and reducing ammonia emissions can have a significant effect on ambient $PM_{2.5}$ levels. The proposed emission reduction for ammonia is significantly smaller than those proposed for other pollutants but compared with the figure of 6% reduction by 2020 in the Gothenburg Protocol (also on a 2005 base) it is definitely ambitious.

A further measure which is crucial to the optimal development of measures to benefit both air quality and climate change is the Eco Design Directive and its implementing regulations, particularly those for solid fuel boilers given the increased use of biomass in small scale appliances (Commission Regulation, 2015). There is a need for more research on real-world emissions of biomass burning appliances to assess the potential impact of the likely increase in biomass burning in urban areas in Europe, and to assess whether or not the emission limits in the Eco Design Directive offer adequate protection for human health.

The European Commission's Clean Air Package was notable for its approach to the Ambient Air Quality Directive (2008/50/EC) where the decision was made to pursue implementation of the current version of the Directive rather than revise the text. The Commission proposed to keep the Directive under review, effectively until the revised NECD was agreed. In the meantime, there have been important developments in the science around the health effects of air pollution, which will be very relevant to a revision of the Ambient Air Directive. The World Health Organisation (WHO) review of the health effects of air pollution, REVIHAAP (WHO, 2013a), concluded that the evidence for adverse effects from PM_{10} and $PM_{2.5}$ was now even stronger than previously and that there was a case for reviewing the existing air quality guidelines. The review concluded that while it was not possible to isolate any component(s) of the PM mix as being responsible for the health effects, it recommended that it would be advantageous to develop an additional air quality guideline to capture the effects of road vehicle PM emissions not adequately captured by $PM_{2.5}$, building on the work on black carbon (Janssen et al 2012) and evidence on other pollutants in vehicle emissions.

REVIHAAP also made some important points on the health effects of NO_2. Previous editions of the WHO Guidelines had noted the fact that epidemiological studies found it difficult to isolate an effect of NO_2 alone, largely due to the close correlation with other traffic emissions, notably PM. The REVIHAAP review concluded that there were now many studies, not previously considered, or published since 2004, which have documented associations between day-to-day variations in NO_2 concentration and variations in mortality, hospital admissions, and respiratory symptoms. Also, more studies have now shown associations between long-term exposure to NO_2 and mortality and morbidity. Both short- and long-term studies have found these associations with adverse effects at concentrations that were at or below the current EU limit values. Chamber and toxicological evidence provides some mechanistic support for a causal interpretation of the respiratory effects. Hence, WHO concluded that the results of these new studies provide support for updating the 2005 WHO air quality guidelines (WHO Regional Office for Europe, 2006) for NO_2, to give: (a) an epidemiologically based short-term guideline value; and (b) an annual average guideline value based on the newly accumulated evidence. In both instances, this could result in lower guideline values.

These conclusions advance the understanding of the health effects of NO_2 considerably and add much support to the case that the non-compliance issue faced by many Member States is also a significant public health problem. This is further supported by the recommendations by WHO in the companion review to REVIHAAP known as HRAPIE (WHO, 2013b) which recommended the use of a relative risk coefficient of 1.055 per $10\mu g/m^3$ of NO_2 concentration for long-term exposure related to cardiovascular mortality.

These recent findings regarding the health effects of NO_2 will not only influence any revision of the Ambient Air Quality Directive but they give added pressure and urgency to the work within the European Commission in defining and promulgating a new regulatory test for real-world emissions from diesel cars. This pressure will also be amplified by the recent revelations of the use of 'defeat devices' by the Volkswagen company in some of its recent diesel car models.

Also Climate policy is at a crucial stage. The 21st Conference of Parties in Paris in December 2015 offers an opportunity for a world-wide agreement on emission reductions, but at this stage it is difficult to predict an outcome. Notwithstanding the final agreement or commitments to reductions in GHG emissions, the methods and pathways to achieving the reductions will be as important as the commitments themselves if adverse effects on air quality and public health are to be avoided, and potential co-benefits are maximised.

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7. References

Altman, A., Amann, M., Klaassen, G., Ruszczyfiski, A., 1996. Cost-effective sulphur emission reduction under uncertainty. European Journal of Operational Research 90, 395-412.

Altaratz, O., Koren, I., Remer, L.A., Hirsch, E., 2014. Review: Cloud invigoration by aerosols—Coupling between microphysics and dynamics. Atmos. Res. 140, 38-60.

Amann, M., 2001. Emission inventories, emission control options and control strategies: an overview of recent developments. Water, Air and Soil Pollution 130, 43-50.

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. Environ. Health Perspect. 120, 831–839.

Arneth, A., Unger N., Kulmala M., Andreae M.O., 2009. Clean the air, heat the planet? Science 326, 672-673.

Ben-Ami, Y., Koren, I., Rudich, Y., Artaxo, P., Martin, S.T., Andreae, M.O., 2010. Transport of North African dust from the Bodèlè depression to the Amazon Basin: a case study. Atmos. Chem. Phys. 10, 7533-7544.

Bond, T.C., Doherty, S.J., Fahey, D.W., Forster, P.M., Berntsen, T., DeAngelo, B.J., Flanner, M.G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P.K., Sarofim, M.C., Schultz, M.G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S.K., Hopke, P.K., Jacobson, M.Z., Kaiser, J.W., Klimont, Z., Lohmann, U., Schwarz, J.P., Shindell, D., Storelvmo, T., Warren, S.G., Zender, C.S., 2013. Bounding the role of black carbon in the climate system: A scientific assessment. J. Geophys. Res. Atmos. 118, 5380-5552.

Boucher, O., Randall, D., Artaxo, P., Bretherton, C., Feingold, G., Forster, P., Kerminen, V.-M., Kondo, Y., Liao, H., Lohmann, U., Rasch, P., Satheesh, S.K., Sherwood, S., Stevens, B., Zhang, X.Y., 2013. Clouds and Aerosols. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge, United Kingdom and New York, NY, USA.

Colette, A., Koelemeijer, R., Mellios, G., Schucht, S., Péré, J.-C., Kouridis, C., Bessagnet, B., Eerens, H., Velze, K.V., Rouïl, L., 2012. Cobenefits of climate and air pollution regulations; The context of the European Commission Roadmap for moving to a low carbon economy in 2050. ETC/ACM Technical Paper 2011/20.

Commission Regulation (EU) 2015/1189 of 28 April 2015 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to eco-design requirements for solid fuel boilers, Official Journal of the European Communities, L 193/100, 21 July 2015.

Davidi, A., Kostinski, A.B., Koren, I., Lehahn, Y., 2012. Observational bounds on atmospheric heating by aerosol absorption: Radiative signature of transatlantic dust. Geophys. Res. Lett. 39, L04803.

Derwent, R.G., Witham, C.S., Utembe, S.R., Jenkin, M.E., Passant, N.R., 2010. Ozone in Central England: the impact of 20 years of precursor emission controls in Europe. Environ. Sci. Policy 13, 195-204.

Dong, H.J., Dai, H.C., Dong, L., Fujita, T., Geng, Y., Klimont, Z., Inoue, T., Bunya, S., Fujii, M., Masui, T., 2015. Pursuing air pollutant co-benefits of CO2 mitigation in China: A provincial leveled analysis. Applied Energy 144 165-174.

Fiore, A.M., Naik V., Spracklen, D.V., Steiner, A., Unger, N., Prather, M., Bergmann, D., Cameron-Smith, P.J., Cionni, I., Collins, W.J., Dalsoren, S., Eyring, V., Folberth, G.A., Ginoux, P., Horowitz, L.W., Josse, B., Lamarque, J.F., MacKenzie, I.A., Nagashima, T., O'Connor, F.M., Righi, M., Rumbold, S.T., Shindell, D.T., Skeie, R.B., Sudo, K., Szopa, S., Takemura, T., Zeng, G., 2012. Global air quality and climate. Chem. Soc. Rev. 41, 6663-6683.

Li, Y., Crawford-Brown, D.J., 2011. Assessing the co-benefits of greenhouse gas reduction: Health benefits of particulate matter related inspection and maintenance programs in Bangkok, Thailand. Science of the Total Environment 409(10) 1774-1785.

Fowler, D., Brunkreef, B., Fuzzi, S., Monks, P. S., Sutton, M. A., Brasseur, G.P., Friedrich, R., Passante, L.G., Jimenez-Mingo, J.M., 2013. Research Findings in support of the EU Air Quality Review, Maione M., and Fuzzi S., Eds. Publications office of the European Union, Luxembourg.

Fuglestvedt, J.S., Shine, K.P., Berntsen, T., Cook, J., Lee, D.S., Stenke, A., Skeie, R.B., Velders, G.J.M., Waitz, I. A., 2010. Transport impacts on atmosphere and climate: Metrics. Atmos. Env. 44, 4648-4677.

Fuzzi, S., Baltensperger, U., Carslaw, K., Decesari, S., Denier van der Gon, H., Facchini, M.C., Fowler, D., Koren, I., Langford, B., Lohmann, U., Nemitz, E., Pandis, S., Riipinen, I., Rudich, Y., Schaap, M., Slowik, J., Spracklen, D.V., Vignati, E., Wild, M., Williams, M., Gilardoni, S., 2015. Particulate matter, air quality and climate: lessons learned and future needs. Atmos. Chem. Phys. 15, 8217-8299.

Hansen, J., Nazarenko, L., 2004. Soot climate forcing via snow and ice albedos. Proc. Natl. Acad. Sci. USA 101, 423-428.

Haywood, J., Boucher, O., 2000. Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: A review. Rev. Geophys. 38, 513-543.

IPCC, 2013: Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.[2]

IPCC: Climate Change 2013 – The Physical Science Basis, Cambridge University Press, Cambridge, 1552 pp., 2013.[3]

Isaksen, I.S.A., Granier, C., Myhre, G., Berntsen, T.K., Dalsoren, S.B., Gauss, M., Klimont, Z., Benestad, R., Bousquet, P., Collins, W., Cox, T., Eyring, V., Fowler, D., Fuzzi, S., Jockel, P., Laj, P., Lohmann, U., Maione, M., Monks, P., Prevot, A.S.H., Raes, F., Richter, A., Rognerud, B., Schulz, M., Shindell, D., Stevenson, D., Storelvmo, T., Wang, W.C., van Weele, M., Wild, M., Wuebbles, D., 2009. Atmospheric composition change: climate–chemistry interactions. Atmos. Environ. 43, 5138-5192.

Jacobson, M.Z., 2012. Investigating cloud absorption effects: Global absorption properties of black carbon, tar balls, and soil dust in clouds and aerosols. J. Geophys. Res. Atmos. 117, D06205.

Janssen, N.A.H., Gerlofs-Nijland, M.E., Lanki, T., Salonen, R.O., Cassee, F., Hoek, G., Fischer, P., Brunekreef, B., Krzyzanowski, M., 2012. Health effects of black carbon. Copenhagen, WHO Regional Office for Europe.

Kim, M.J., Park, R.J., Ho, C.H., Woo, J.H., Choi, K.C., Song, C.K., Lee, J.B., 2015. Future ozone and oxidants change under the RCP scenarios. Atmos. Env. 101, 103-115.

Koch, D., Del Genio, A., 2010. Black carbon semi-direct effects on cloud cover: review and synthesis. Atmos. Chem. Phys. 10, 7685-7696.

Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., Pozzer, A., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature 525, 367–371.

Lim, S.S., Vos, T., Flaxman, A.D., Danaei, G., Shibuya, K., Adair-Rohani, H., Amann, M., Anderson, H.R., Andrews, K.G., Aryee, M., Atkinson, C., Bacchus, L.J., Bahalim, A.N., Balakrishnan, K., Balmes, J., Barker-Collo, S., Baxter, A., Bell, M.L., Blore, J.D., Blyth, F., Bonner, C., Borges, G., Bourne, R., Boussinesq, M., Brauer, M., Brooks, P., Bruce, N.G., Brunekreef, B., Bryan-Hancock, C., Bucello, C., Buchbinder, R., Bull, F., Burnett, R.T., Byers, T.E., Calabria, B., Carapetis, J., Carnahan, E., Chafe, Z., Charlson, F., Chen, H., Chen, J.S., Cheng, A.T.-A., Child, J.C., Cohen, A., Colson, K.E., Cowie, B.C., Darby, S., Darling, S., Davis, A., Degenhardt, L., Dentener, F., Des Jarlais, D.C., Devries, K., Dherani, M., Ding, E.L., Dorsey, E.R., Driscoll, T., Edmond, K., Ali, S.E., Engell, R.E., Erwin, P.J., Fahimi, S., Falder, G., Farzadfar, F., Ferrari, A., Finucane, M.M., Flaxman, S., Fowkes, F.G.R., Freedman, G., Freeman, M.K., Gakidou, E., Ghosh, S., Giovannucci, E., Gmel, G., Graham, K., Grainger, R., Grant, B., Gunnell, D., Gutierrez, H.R., Hall, W., Hoek, H.W., Hogan, A., Hosgood III, H.D., Hoy, D., Hu, H., Hubbell, B.J., Hutchings, S.J., Ibeanusi, S.E., Jacklyn, G.L., Jasrasaria, R., Jonas, J.B., Kan, H., Kanis, J.A., Kassebaum, N., Kawakami, N., Khang, Y.-H., Khatibzadeh, S., Khoo, J.-P., Kok, C., Laden, F., Lalloo, R., Lan, Q., Lathlean, T., Leasher, J.L., Leigh, J., Li, Y., Lin, J.K., Lipshultz, S.E., London, S., Lozano, R., Lu, Y., Mak, J., Malekzadeh, R., Mallinger, L., Marcenes, W., March, L., Marks, R., Martin, R., McGale, P., McGrath, J., Mehta, S., Mensah, G.A., Merriman, T.R., Micha, R., Michaud, C., Mishra, V., Hanafiah, K.M., Mokdad, A.A., Morawska, L., Mozaffarian, D., Murphy, T., Naghavi, M., Neal, B., Nelson, P.K., Nolla, J.M., Norman, R., Olives, C., Omer, S.B., Orchard, J., Osborne, R., Ostro, B., Page, A., Pandey, K.D., Parry, C.D.H., Passmore, E., Patra, J., Pearce, N., Pelizzari, P.M., Petzold, M., Phillips, M.R., Pope, D., Pope III, C.A., Powles, J., Rao, M., Razavi, H., Rehfuess, E.A., Rehm, J.T., Ritz, B., Rivara, F.P., Roberts, T., Robinson, C., Rodriguez-Portales, J.A., Romieu, I., Room, R., Rosenfeld, L.C., Roy, A., Rushton, L., Salomon, J.A., Sampson, U., Sanchez-Riera, L., Sanman, E., Sapkota, A., Seedat, S., Shi, P., Shield, K., Shivakoti, R., Singh, G.M., Sleet, D.A., Smith, E., Smith, K.R., Stapelberg, N.J.C., Steenland, K., Stöckl, H., Stovner, L.J., Straif, K., Straney, L., Thurston, G.D., Tran, J.H., Van Dingenen, R., Van Donkelaar, A., Veerman, J.L., Vijayakumar, L., Weintraub, R., Weissman, M.M., White, R.A., Whiteford, H., Wiersma, S.T., Wilkinson, J.D., Williams, H.C., Williams, W., Wilson, N., Woolf, A.D., Yip, P., Zielinski, J.M., Lopez, A.D., Murray, C.J.L., Ezzati, M., 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease 2010. The Lancet 380, 2224-2260.

Lohmann, U., Feichter, J., 2005. Global indirect aerosol effects: a review. Atmos. Chem. Phys. 5, 715-737.

Liu, F., Klimont, Z., Zhang, Q., Cofala, J., Zhao, L.J., Huo, H., Nguyen, B., Schopp, W., Sander, R., Zheng, B., Hong, C.P., He, K.B., Amann, M., Heyes, C., 2013. Integrating mitigation of air pollutants and greenhouse gases in Chinese cities: development of GAINS-City model for Beijing. Journal of Cleaner Production 58 25-33.

Mahowald, N., 2011. Aerosol indirect effect on biogeochemical cycles and climate. Science 334, 794-796.

Matus, K., Yang, T., Paltsev, S., Reilly, J., Nam, K.M., 2008. Toward integrated assessment of environmental change: air pollution health effects in the USA. Climatic Change 88(1) 59-92.

Menon, S., Hansen, J., Nazarenko, L., Luo, Y., 2002. Climate Effects of Black Carbon Aerosols in China and India. Science 297, 2250-2253.

Mishra, A.K., Klingmueller, K., Fredj, E., Lelieveld, J., Rudich, Y., Koren, I., 2014. Radiative signature of absorbing aerosol over the eastern Mediterranean basin. Atmos. Chem. Phys. 14, 7213-7231.

Mittal, S., Hanaoka, T., Shukla, P.R., Masui, T., 2015. Air pollution co-benefits of low carbon policies in road transport: a sub-national assessment for India. Environmental Research Letters 10(8).

Monks, P.S., 2000. A review of the observations and origins of the spring ozone maximum. Atmos. Env. 34, 3545-3561.

Monks, P.S., Archibald, A.T., Colette, A., Cooper, O., Coyle, M., Derwent, R., Fowler, D., Granier, C., Law, K.S., Mills, G.E., Stevenson, D.S., Tarasova, O., Thouret, V., von Schneidemesser, E., Sommariva, R., Wild, O., Williams, M.L., 2015. Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer. Atmos. Chem. Phys. 15, 8889-8973.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T. Zhang, H., 2013. Anthropogenic and Natural Radiative Forcing, in: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.[4]

Myhre, G., Samset, B.H., Schulz, M., Balkanski, Y., Bauer, S., Berntsen, T.K., Bian, H., Bellouin, N., Chin, M., Diehl, T., Easter, R.C., Feichter, J., Ghan, S.J., Hauglustaine, D., Iversen, T., Kinne, S., Kirkevåg, A., Lamarque, J.-F., Lin, G., Liu, X., Lund, M.T., Luo, G., Ma, X., van Noije, T., Penner, J.E., Rasch, P.J., Ruiz, A., Seland, Ø., Skeie, R.B., Stier, P., Takemura, T., Tsigaridis, K., Wang, P., Wang, Z., Xu, L., Yu, H., Yu, F., Yoon, J.-H., Zhang, K., Zhang, H., Zhou, C., 2013. Radiative forcing of the direct aerosol effect from AeroCom Phase II simulations. Atmos. Chem. Phys. 13, 1853-1877.[5]

Nazarenko, L., Schmidt, G.A., Miller, R.L., Tausnev, N., Kelley, M., Ruedy, R., Russell, G.L., Aleinov, I., Bauer, M., Bauer, S., Bleck, R., Canuto, V., Cheng, Y., Clune, T.L., Del Genio, A.D., Faluvegi, G., Hansen, J.E., Healy, R.J., Kiang, N.Y., Koch, D., Lacis, A.A., LeGrande, A.N., Lerner, J., Lo, K.K., Menon, S., Oinas, V., Perlwitz, J., Puma, M.J., Rind, D., Romanou, A., Sato M., Shindell, D.T., Sun, S., Tsigaridis, K., Unger, N., Voulgarakis, A., Yao, M.-S., Zhang, J., 2015. Future climate change under RCP emission scenarios with GISS ModelE2. Journal of Advances in Modeling Earth Systems 7, 244-267.

Ramanathan, V., Carmichael, G., 2008. Global and regional climate changes due to black carbon. Nature Geoscience 1, 221-227.

Ramanathan, V., Feng, Y., 2009. Air pollution, greenhouse gases and climate change: Global and regional perspectives. Atmos. Environ. 43, 37-50.

Rasmussen, D.J., Hu, J.L., Mahmud, A., Kleeman, M.J., 2013. The Ozone-Climate Penalty: Past, Present, and Future. Environ. Sci. Technol. 47, 14258-14266.

Reis, S., Grennfelt, P., Klimont, Z., Amann, M., ApSimon, H., Hettelingh, J.-P., Holland, M., LeGall, A.-C., Maas, R., Posch, M., Spranger, T., Sutton, M.A., Williams, M., 2012. From Acid Rain to Climate Change. Science 338, 1153-1154.

Reis, S., Nitter, S., Friedrich, R., 2005. Innovative Approaches in Integrated Assessment Modelling of European Air Pollution Control Strategies – Implications of Dealing with Multi-pollutant Multi-effect Problems. Environmental Modelling and Software 20, 1524–1531.

Remais, J.V., Hess, J.J., Ebi, K.L., Markandya, A., Balbus, J.M., Wilkinson, P., Haines, A., Chalabi, Z., 2014. Estimating the Health Effects of Greenhouse Gas Mitigation Strategies: Addressing Parametric, Model, and Valuation Challenges. Environmental Health Perspectives 122(5) 447-455.

Rogelj, J., Schaeffer, M., Meinshausen, M., Shindell, D.T., Hare, W., Klimont, Z., Velders, G.J.M., Amann, M. Schellnhuber, H.J., 2014. Disentangling the effects of CO2 and short-lived climate forcer mitigation. Proc. Natl. Acad. Sci. USA, 111 16325-16330

Shindell, D., Kuylenstierna, J.C.I., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S.C., Muller, N., Janssens-Maenhout, G., Raes, F., Schwartz, J., Faluvegi, G., Pozzoli, L., Kupiainen, K., Höglund-Isaksson, L., Emberson, L., Streets, D., Ramanathan, V., Hicks, K., Oanh, N.T.K., Milly, G., Williams, M., Demkine, V., Fowler, D., 2012. Simultaneously mitigating near-term climate change and improving human health and food security. Science 335, 183–189.

Shindell, D.T., 2015. The social cost of atmospheric release. Climatic Change 130, 313-326.

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. Chem. Rev. 115, 3856-3897.

von Stechow, C., McCollum, D., Riahi, K., Minx, J.C., Kriegler, E., van Vuuren, D.P., Jewell, J., Robledo-Abad, C., Hertwich, E., Tavoni, M., Mirasgedis, S., Lah, O., Roy, J., Mulugetta, Y., Dubash, N.K., Bollen, J., Urge-Vorsatz, D., Edenhofer, O., 2015. Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. Annual Review of Environment and Resources, Vol 40 40 363-+.

Schucht, S., Colette, A., Rao, S., Holland, M., Schopp, W., Kolp, P., Klimont, Z., Bessagnet, B., Szopa, S., Vautard, R., Brignon, J.M., Rouil, L., 2015. Moving towards ambitious climate policies: Monetised health benefits from improved air quality could offset mitigation costs in Europe. Environmental Science & Policy 50 252-269.

Simpson, D., Arneth, A., Mills, G., Solberg, S., Uddling, J., 2014. Ozone — the persistent menace: interactions with the N cycle and climate change. Current Opinion in Environmental Sustainability 9-10, 9-19.

Solenkova, N.V., Newman, J.D., Berger, J.S., Thurston, G., Hochman, J.S., Lamas, J.A., 2014. Metal pollutants and cardiovascular disease: Mechanisms and consequences of exposure. American Heart Journal 168, 812–822.

Stevenson, D.S., Young, P.J., Naik, V., Lamarque, J.F., Shindell, D.T., Voulgarakis, A., Skeie, R.B., Dalsoren, S.B., Myhre, G., Berntsen, T.K., Folberth, G.A., Rumbold, S.T., Collins, W.J., MacKenzie, I.A., Doherty, R.M., Zeng, G., van Noije, T.P.C., Strunk, A., Bergmann, D., Cameron-Smith, P., Plummer, D.A., Strode, S.A., Horowitz, L., Lee, Y.H., Szopa, S., Sudo, K., Nagashima, T., Josse, B., Cionni, I., Righi, M., Eyring, V., Conley, A., Bowman, K.W., Wild, O., Archibald, A., 2013. Tropospheric ozone changes, radiative forcing and attribution to emissions in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP). Atmos. Chem. Phys. 13, 3063-3085.

Stier, P., Seinfeld, J.H., Kinne, S., Boucher, O., 2007. Aerosol absorption and radiative forcing. Atmos. Chem. Phys. 7, 5237-5261.

Stocker, T.F., Qin, D., Plattner, G.-K., Alexander, L.V., Allen, S.K., Bindoff, N.L., Bréon, F.-M., Church, J.A., Cubasch, U., Emori, S., Forster, P., Friedlingstein, P., Gillett, N., Gregory, J.M., Hartmann, D.L., Jansen, E., Kirtman, B., Knutti, R., Krishna Kumar, K., Lemke, P., Marotzke, J., Masson-Delmotte, V.,. Meehl, G.A, Mokhov, I.I., Piao, S., Ramaswamy, V., Randall, D., Rhein, M., Rojas, M., Sabine, C., Shindell, D., Talley, L.D.,

Stohl, A., Aamaas, B., Amann, M., Baker, L.H., Bellouin, N., Berntsen, T.K., Boucher, O., Cherian, R., Collins, W., Daskalakis, N., Dusinska, M., Eckhardt, S., Fuglestvedt, J.S., Harju, M., Heyes, C., Hodnebrog, O., Hao, J., Im, U., Kanakidou, M., Klimont, Z., Kupiainen, K., Law, K.S., Lund, M.T., Maas, R., MacIntosh, C.R., Myhre, G., Myriokefalitakis, S., Olivie, D., Quaas, J., Quennehen, B., Raut, J.C., Rumbold, S.T., Samset, B.H., Schulz, M., Seland, O., Shine, K.P., Skeie, R.B., Wang, S., Yttri, K.E., Zhu, T., 2015. Evaluating the climate and air quality impacts of short-lived pollutants. Atmospheric Chemistry and Physics 15(18) 10529-10566.

Tollefsen, P., Rypdal, K., Torvanger, A., Rive, N., 2009. Air pollution policies in Europe: efficiency gains from integrating climate effects with damage costs to health and crops. Environmental Science & Policy 12(7) 870-881.

Vaughan, D.G., Xie, S.-P., 2013. Technical Summary. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge, United Kingdom and New York, NY, USA, 2013.

Swedish EPA: Air Pollution and Climate Change - Two sides of the same coin? Swedish Environmental Protection Agency, Solna - Sweden, 2009.

UNEP-WMO, 2011: Integrated Assessment of Black Carbon and Tropospheric Ozone, UNON Publishing Services Section, Nairobi, Kenia.

Urge-Vorsatz, D., Herrero, S.T., Dubash, N.K., Lecocq, F., 2014. Measuring the Co-Benefits of Climate Change Mitigation. Annual Review of Environment and Resources, Vol 39 39 549-582.

Van Grinsven, H.J.M., Holland, M., Jacobsen, B.H., Klimont, Z., Sutton, M.A., Willems, W.J.,2013. Costs and benefits of nitrogen for Europe and implications for mitigation. Environ. Sci. Technol. 47, 3571–3579.

Voulgarakis, A., Naik, V., Lamarque, J.-F., Shindell, D.T., Young, P.J., Prather, M.J., Wild, O., Field, R.D., Bergmann, D., Cameron-Smith, P., Cionni, I., Collins, W.J., Dalsøren, S.B., Doherty, R.M., Eyring, V., Faluvegi, G., Folberth, G.A., Horowitz, L.W., Josse, B., MacKenzie, I.A., Nagashima, T., Plummer, D.A., Righi, M., Rumbold, S.T., Stevenson, D.S., Strode, S.A., Sudo, K., Szopa, S., Zeng, G., 2013. Analysis of present day and future OH and methane lifetime in the ACCMIP simulations. Atmos. Chem. Phys. 13, 2563-2587.

WHO (World Health Organization) 2013a, Review of evidence on health aspects of air pollution –REVIHAAP Project: Final technical report. WHO Regional Office for Europe. Available at: http://www.euro.who.int/en/what-we-do/health-topics/environment-andhealth/air-quality/publications/2013/review-of-evidence-on-healthaspects-of-air-pollution-revihaap-project-final-technical-report .

WHO (World Health Organization) 2013b, Health risks of air pollution in Europe – HRAPIE project; Recommendations for concentration–response functions for cost–benefit analysis of particulate matter, ozone and nitrogen dioxide; WHO Regional office for Europe. Available at 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

WHO (World Health Organization) Regional Office for Europe, OECD (Organisation for Economic Co-operation and Development), 2015. Economic cost of the health impact of air pollution in Europe: Clean air, health and wealth. Copenhagen: WHO Regional Office for Europe.

Wu, S.L., Mickley, L.J., Leibensperger, E.M., Jacob, D.J., Rind, D., Streets, D.G., 2008. Effects of 2000-2050 global change on ozone air quality in the United States. J. Geophys. Res. Atmos. 113, D18312.

Zusman, E., Miyatsuka, A., Evarts, D., Oanh, N.K., Klimont, Z., Amann, M., Suzuki, K., Mohammad, A., Akimoto, H., Romero, J., Hannan Khan, S.M., Kuylenstierna, J., Hicks, K., Ajero, M., Patdu, K., 2013. Co-benefits: taking a multidisciplinary approach. Carbon Manag 4, 135-137.