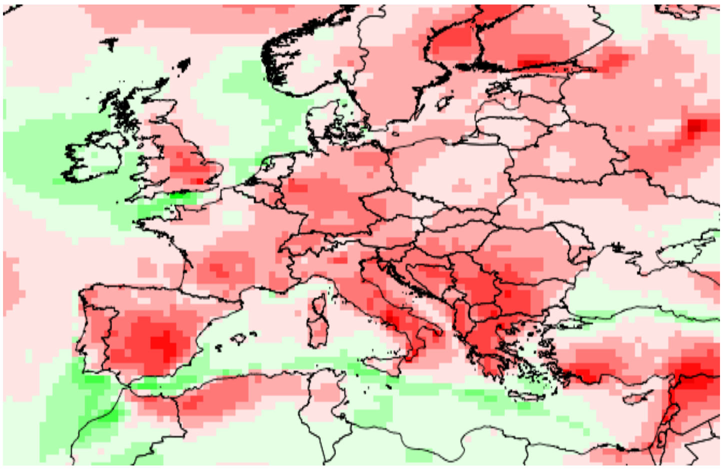
Role of low carbon scenarios on 2050 European air quality and radiative forcing



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Front page picture:
Climate penalty bearing upon surface ozone in 2050 in the business as usual scenario (red when climate has a negative impact on ozone pollution, i.e. tends to increase O3 levels).

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Contents

Abstract

The impacts of climate policies on air quality are twofold. First, climate policies imply energy efficiency measures and other technical measures that will have an impact on a wide range of human activities, emissions, and, in turn, on air quality. Second, air quality is sensitive to climate change (which affects physical and chemical properties of the atmosphere) and long range transport of background pollution. Measures designed to mitigate climate change and their effectiveness will thus have both direct and indirect impacts on air pollution.

To quantify changes in air pollution in Europe resulting from climate policies at the 2050 horizon, we designed a comprehensive modelling system that captures the external factors considered to be most important for air quality and which relies on the latest set of air pollution and climate scenarios. Climate simulations rely on the recent Representative Concentrations Pathways (RCP) of IPCC whereas air quality modelling is based on the emissions produced in the framework of the more recent Global Energy Assessment. In both cases, we explored two scenarios that are consistent in the climate and air quality models in terms of policy measures: a reference in which climate policies are absent and a mitigation scenario which will limit global temperature rise to within 2 degrees Celsius by the end of this century.

The results are presented in terms of indicators that are relevant regarding the impact of air pollution on health and vegetation. Furthermore attention is given to the de-convolution of the respective contribution of changes in European emissions, hemispheric background concentrations and climate conditions. Acknowledging that the benefit of using a comprehensive regional climate and air quality modelling system is accompanied by an increased opacity of the modelling chain, a synthetic indicator is designed to quantify the respective impact of each compartment. This new indicator allows isolating the net effect of climate change on air quality, as well as the contributions of anthropogenic emission changes and long range transport.

The key findings of the study are:

- European PM2.5 concentrations will strongly decrease by 2050 (by some 60%-70%), largely because of current air quality policies. The effect of climate change and changing hemispheric background concentrations on European PM2.5 concentrations is significant yet of second order compared to the effect of European emission changes of air pollutants.
- Maximum ozone concentrations in Europe in 2050 will be lower than current levels in both scenarios. In the mitigation scenario, maximum ozone levels decrease by some 35% while it decreases by about 10% in the reference scenario. The change in maximum ozone concentrations is dominated by changes in European emissions of air pollutants, but is also significantly affected by climate change and changes in hemispheric background concentrations.

- The decrease of PM2.5 concentrations will imply a reduction by a factor two of the net cooling effect of PM2.5 in terms of radiative forcing over Europe hence constituting a penalty against planned climate policy, although a more representative assessment of this penalty will be published in 2013 at the global scale in the forthcoming IPCC report.
- While ammonia emissions do not decrease in the scenarios, secondary inorganic aerosol concentrations do decrease because of the strongly decreasing NOx emissions which limit ammonium nitrate formation.
- Average ozone maxima will decrease under all scenarios. However, for the reference scenario compensation between climate and emission trends is such that the trends differ in sign for the ozone exposure indicator relevant for human health (SOMO35, which increases), and that for vegetation (AOT40, which decreases); thereby illustrating the limited net signal in the scenario assuming no specific climate policy.
- A changing climate leads to higher ozone concentrations under both scenarios. However the calculated ozone increase according to the regional air quality and climate modelling system implemented here is smaller for the most pessimistic trajectory (RCP8.5), indicating that the impact of climate change on ozone is more complicated than what might be expected from considerations of changes in average temperature. Besides a higher global warming, the RCP8.5 is also accompanied by a number of changes in atmospheric flow patterns (weather regime, magnitude of heat waves, frequency of mid-latitude low pressure systems) that affect ozone levels as well.
- The impact of climate change is found to be of the same order of magnitude for particulate matter as for ozone levels in Europe (in terms of its contribution to the relative annual average concentration change). Preliminary findings using the new indicator of climate change impact on PM2.5 concentrations show a net benefit for PM2.5 in the pessimistic climate scenario and a penalty for PM2.5 the low carbon scenario. These differences are attributed to changes in weather regimes in each scenario, as well as potential impact of higher temperature on the inhibition of the formation of secondary inorganic particles such as ammonium nitrate. It should be noted however that these results are preliminary and would be strengthened by using longer sensitivity tests and an ensemble of models.

Even though the modelling suite offers a high degree of consistency and relies on recent scenarios, it should be emphasized that it relies on a single suite of models. There is an important spread amongst the different model proposing global climate projections, and even more so for regional climate projection and the results included in the present report rely on a single realisation of such simulations. The key messages above would gain in robustness if they were obtained with an ensemble of models as is common practice in model projection exercises.

1 Introduction

Air quality and climate are closely inter-related in their functioning, their mitigation policies, and their impacts (EEA, 2004a):

- Many technological and energy efficiency measures designed to reduce the emissions of greenhouse gases induce indirectly a change in the emission of air pollutants and precursors.
- Climate and air quality are affected by the same atmospheric processes, both with respect to physics and chemistry.
- Climate change may alter the frequency of extreme weather events such heat waves and cold spells that may lead to major air pollution events.
- Many air pollutants (both gaseous and particulate) have direct and indirect impacts on climate through the radiative balance of the atmosphere.

Air quality projections constitute an essential piece of information in the design of future mitigation strategies. In Europe, the GAINS modelling framework (Amann et al., 2011; Amann and Lutz, 2000) is used extensively to support the design of cost-effective measures. The optimisation core of GAINS is based on a number of source-receptor sensitivity simulations with the EMEP chemistry-transport model (Simpson et al., 2012) exploring the impact on air quality of an incremental change in emissions. These sensitivity simulations were validated for mid-term projections (about 20 years) by comparison with a larger ensemble of air quality models (Cuvelier et al., 2007; van Loon et al., 2007; Colette et al., 2012a). However their relevance for longer term projections (50 years) is challenged by the lack of climate impacts and magnitude of the expected changes in emissions (if they exceed the range explored in the sensitivity simulations).

Recent studies that investigated the sensitivity of regional air quality to altered climate forcing (Andersson and Engardt, 2010; Katragkou et al., 2011; Langner et al., 2012; Meleux et al., 2007; Manders et al., 2012) confirmed the penalty brought about by future climate on ozone exposure. Only (Langner et al., 2012) discussed the attribution of the relative change to climate and anthropogenic emission changes and found a dominating effect of later. And only one study (Manders et al., 2012) included a detailed analysis of projected exposure to particulate matter at the regional scale in a changing climate context.

The above studies relied on climate projection of the past iteration of the IPCC assessment reports and neglected changes in background (global) chemical environment. We propose to fill this gap in the present report by implementing a regional environmental modelling system that offers a higher degree of consistency, making use of the last generation of forcing fields, and focusing on ozone and particulate matter exposure in a joint manner.

In 2011, we reviewed available climate policy scenarios and assessed their impact on European air quality in 2030 (Colette et al., 2011). The present report expands upon this work by discussing the role of low carbon scenarios on 2050 European air quality and radiative forcing. To achieve this, a modelling experiment compliant with the highest standard of state of the art methodologies and input data was designed:

- Mitigation: The emission projections of long-lived greenhouse gases (CO2, CH4, N2O, etc.) used to drive the climate (global and regional) projections are the Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011) that are used in the forthcoming fifth IPCC Assessment report. Chemically active air pollutant emission projections (NOx, VOC, primary particulate matter, ammonia, sulphur dioxide, etc.) used in the air quality simulations are obtained from the Global Energy Assessment: compliant with the radiative forcing targets of the RCPs but including more refined emission factors to represent the current air quality legislation (Riahi et al., 2012).
- Atmospheric modelling: The air quality modelling relies on CHIMERE (Bessagnet et al., 2008a), a state of the art regional chemistry transport model used in a number of international coordinated experiment. As an offline model, CHIMERE requires boundary conditions that were extracted from the latest set of simulations performed for the forthcoming IPCC assessment.
- Impacts: The results are presented in an exposure-based framework to highlight the expected impacts on health, ecosystems and climate.

This report is structured as follows. Chapter 2 is devoted to the introduction of the modelling context, with emphasis on the input data (emissions, climate and chemical background forcing). The modelling results are discussed in Chapter 3, while Chapter 4 includes an overview of the climate penalty/benefit indicator that can be derived from these simulations.

2 Drivers of the modelling experiments

2.1 Introduction

This section reviews the main input data for the regional Chemistry-Transport Modelling (CTM). As will be emphasized in the following subsections, particular emphasis was given in the design of the modelling experiment on the use of the latest source of information in the input data with regards to emission scenario and consistency throughout the models involved.

2.2 Emission inventories:

In the framework of the Global Energy Assessment (GEA), four scenarios were developed (Riahi et al., 2012). These scenarios are now publicly available on the website of the GEA initiative[1]. They are based on modelling by IIASA with MESSAGE (energy system) and GAINS (air quality). Information about air pollutant inventories and air quality legislation (control options) from GAINS was linked with the MESSAGE energy scenarios to derive sector based estimates of air pollutant emissions.

MESSAGE distinguishes 11 world regions, amongst which Western Europe and Central & Eastern Europe. The emissions are subsequently spatialised using ACCMIP emission data for the year 2005 (Lamarque et al., 2010). The following greenhouse gases and air pollutants are included in the scenarios, of which all but CO_2 were gridded: CO_2, CH_4, SO_2, NOx, CO, VOCs, BC, OC, PM2.5.

The emission trajectories were developed for the period from 2005 up to 2100. The main focus of the scenarios, however, is on 2030 after that date environmental Kuznets coefficients are applied to represent Air Quality (AQ) policies.

Out of the four GEA scenarios, we focus on the two median trajectories that include the same – current – air quality legislation (cf. **Table 1**) but two levels of policies towards climate change and energy efficiency and access. Whereas the reference scenario assumes no specific climate policy, the mitigation scenario assumes policies leading to a stabilisation of global warming (2°C target) in 2100. The major policy assumptions behind these two GEA scenarios are summarised in Table 2.

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[1] http://www.iiasa.ac.at/Research/ENE/GEA/index_gea.html

Compared to the reference, the mitigation scenario is characterised by a distinctly lower energy demand and shifts in the energy mix (less coal/oil and more renewables). Energy demand increases globally until 2100 across all the scenarios, although in the climate mitigation scenarios demand growth is very limited and global energy use stabilizes by the end of the century. For specific regions, however, energy demand declines in the mitigation scenario because of the much larger emission intensity improvements compared to the rest of the world. For Europe this is the case from 2010 onwards.

	Transport (except shipping)	**Industry and power sector**	**Shipping**	**Other sectors**
SO_2	OECD: directives on the sulphur content in liquid fuels; directives on quality of petrol and diesel fuels. Non-OECD: national directives on the sulphur content in liquid fuels	OECD: emission standards for new plants from the Industrial Emissions Directive (IED) Non-OECD: increased use of low sulphur coal, increasing penetration of FGD after 2005 in new and existing plants	MARPOL Annex VI regulations	Reduction in gas flaring, reduction in agricultural waste burning
NOx	OECD: emission controls for vehicles and off-road sources up to the Euro-VI and Euro-V standard; penetration of three-way catalysts Non-OECD: national emission standards equivalent to up to Euro III-IV standards	OECD: Emission limits according to the EU IED; national emission standards if stricter that IED Non-OECD: primary measures for controlling NOx	Revised MARPOL Annex VI regulations	Reduction in gas flaring, reduction in agricultural waste burning
CO	OECD: emission controls for vehicles and off-road sources up to the Euro-VI and Euro-V standard; penetration of three-way catalysts			Reduction in gas flaring, reduction in agricultural waste burning
VOC	Stage-I measures	Solvent directive		Reduction in

		of the EU (COM(96), 538, 1997); 1994 VOC protocol of the LRTAP convention		gas flaring, reduction in agricultural waste burning
NH_3		End of pipe controls in industry (fertilizer manufacturing)		

Table 1 : Specific policies and measures for air pollution control in the CLE scenarios. Source: (Riahi et al., 2012).

Scenario	**Policies**			
	Air pollution	Climate Change	Energy efficiency	Energy access
Reference Case with Current Legislation (CLE) [Reference]	All current and planned air quality legislations until 2030 Kuznets theory beyond 2030	No climate policy	Annual energy intensity reduction of 1.5% until 2050	No specific energy access policy; medium improvement in quality of cooking fuels
Sustainable Policy with CLE [mitigation]	All current and planned air quality legislations until 2030 Kuznets theory beyond 2030	Limit on temperature change to 2°C in 2100	Annual energy intensity reduction of 2.6% until 2050	Policies to ensure global access to clean energy by 2060

Table 2 : Scenario Policy Matrix. Source: (Riahi et al., 2012).

2.3 Regional Climate Modelling (RCM):

Offline regional air quality models are driven by prescribed meteorological fields. For most air quality assessment studies, reanalyses of past climate that benefit from assimilation procedure (and therefore exhibit small biases) are used. But for future projection work, the use of meteorological fields resulting from climate models is required. Coupled global models delivering such climate projections are widely documented in the literature, and the reader is referred to the latest IPCC assessment (IPCC, 2007) and the description of the forthcoming Climate Model Intercomparison Project (CMIP) (Taylor et al., 2012) for further details.

Of particular interest for climate impact studies is the issue of Regional Climate Modelling. Climate impact studies such as studies addressing food safety, meteorological and hydrological extremes, impacts on health and ecosystems require climate data at a spatial resolution higher than the few hundred of kilometre grid cells in the CMIP models. For some of such impact studies statistical downscaling of ground-level climate parameters is sufficient. However for some applications such as air quality or hydrological extremes, a downscaling of the full 3D fields of the climate models is required. Therefore in that case a regional climate model is preferred to statistical approaches to produce a refined projection.

As far as Europe is concerned, regional climate modelling initiatives have been coordinated over the last decade through the PRUDENCE, ENSEMBLES and CORDEX experiments (the focus of the later including also other regions of the world beyond Europe). In the framework of each of these projects, a number of mesoscale climate models were implemented in a coordinated manner to document the spread of the models as well as forcing constrains (global models, emission projections, etc.). Given the sensitivity of regional air quality projections to the underlying regional climate model, we summarize in this section the main findings of previous initiative related to climate change projection in Europe in order to have a better insight on the uncertainties brought about by the RCM in the overall projection modelling system.

PRUDENCE (Christensen et al., 2007) was the first initiative in the early 2000's to produce 30 years time-slices simulations corresponding to the recent past and the end of the 21st century with regional climate models at about 50km resolution. The validation of the ensemble over the recent past showed that the models tend to produce a warm bias in summer and winter with a more limited cold bias in the transition seasons, and that these biases were larger for extreme warm and low temperatures (Jacob et al., 2007). The regional models were found to be less sensitive to the boundary conditions derived from global models in summer, highlighting the role of internal processes (such as the land surface models) for that season, whereas synoptic scale processes dominate in winter (Christensen and Christensen, 2007). For the same reason, the year to year variability was overestimated in summer (Jacob et al., 2007) and all the models projected an increase in the variability in the future (Vidale et al., 2007) even though the model spread was reduced in the prospective scenario compared to the control historical simulations (Christensen and Christensen, 2007).

ENSEMBLES was an opportunity to expand the work initiated in PRUDENCE by increasing the time period, producing transient simulations, investigating a larger array of large scale boundary conditions, etc. Some regional models were forced by several different global climate models which led to the conclusion that the spread between the scenarios was somewhat dominated by the spread between the boundary conditions obtained from global climate models. It was only by the end of the 21st century that the differences between the scenarios exceeded the variability of the regional and global models (Kjellström et al., 2011).

The current exercise, CORDEX (Giorgi et al., 2009) builds upon previous expertise and offers a framework for downscaling the latest CMIP5 global climate model results in a coordinated way for different regions of the world. This initiative is supported by the World Climate Research Programme. The European simulations are conducted in the EURO-CORDEX consortium (Gobiet and Jacob, 2012) and include the added value compared to the rest of the world to aim at a resolution of about 12km over Europe for long term regional climate projections.

The first evaluation papers were published or submitted in 2012. Two of them included diagnostics that are especially relevant for air quality impact studies. By focusing on an ensemble of six models having delivered a 12km hindcast of the past 20 years, (Vautard et al., 2012) concluded that the regional models tend to overestimate heat waves in magnitude when forced with reanalyses as well as persistence. (Menut et al., 2012) confirmed this tendency to overestimate stagnant episodes (and therefore pollution episodes) all year round in a preliminary version of the regional climate simulations used in the present report (Section 3).

Beyond the investigation of the ability of regional models to capture climate variability, most of the above cited papers rely on ensembles to minimise biases, whereas individual climate models often exhibit biases in temperature as high as 2 to 4K (Kjellström et al., 2011; Menut et al., 2012). Such numbers raise obvious concerns for climate impact studies, in the context of air quality a difference of a few degrees can induce quite a large impact on the ozone productivity (Menut, 2003). This sensitivity is also emphasized in a recent paper by (Manders et al., 2012) who found that the difference between a the regional climate model and the reanalysis for the recent past could exceed the difference between current and projected climate by 2050.

A provisional solution to cope with this limitation consists in focussing on relative changes rather than absolute values. For the present report we indeed use raw model output without any bias correction and work in a relative framework.

A more satisfactory alternative for impact studies would be to rely on a variety of regional climate simulations (i.e., use an ensemble approach). However, because of computational constrains, such a demanding initiative has not been undertaken yet. Another option consists in correcting biases in the regional climate projection. There are techniques to produce unbiased projections of regional climate parameters at the surface such as temperature and precipitation (Déqué, 2007; Vrac et al., 2007), but these approaches are not relevant for air quality modelling that requires unbiased 3D atmospheric fields. The most promising option currently available consists in performing an upstream correction of the global climate model before performing the regional climate modelling projection. By applying this technique over the recent past (Colette et al., 2012c) could reduce the temperature bias of a regional climate projection from -5.1K down to -1.4 K. Such calibrated regional climate models remains to be performed for future projections and are therefore not used in the results presented below.

To sum up, climate impact studies at the regional scale benefit today from a decade of research on the capacity of regional models to capture the European climate. There is now a well coordinated community of regional climate researchers that produces simulations that can be made available for the purpose of impact investigations in a similar way as being done at the global scale in the IPCC framework. The results of these coordinated projects were used in the past for air quality projections: PRUDENCE in (Meleux et al., 2007), ENSEMBLES in (Katragkou et al., 2011; Langner et al., 2012), EUROCORDEX (this report, Section 3). However it is essential to keep in mind the uncertainties related to climate modelling at the regional scale and the potential consequences for impact studies.

2.4 Chemical boundary conditions

Regional Chemistry Transport modelling requires the prescription of background concentrations at the boundaries of the domain and at the initialisation of the simulation. Boundary conditions are needed in particular to capture the trend in background pollution transported over long distance.

Two options are available for the prescription of boundary conditions in regional models: using a climatology derived from an average of past observations or input fields provided by global models. Using observations allows minimising potential biases of the global models. However the representativeness of observations is limited in space and time, and observations are only available for a limited number of species. Nevertheless, because of its robustness, observation-based boundary conditions is the methodology used for the policy underpinning simulations of the EMEP model (Simpson et al., 2012).

In the context of future projections, such an approach reaches obvious limits. Hence, input from global chemistry models is preferred. In order to benefit from the latest generation of global chemistry models we use here the results of the recent ACCMIP exercise (Atmospheric Composition Change Model Intercomparison Project, (Lamarque et al., 2012)).

2.4.1 Atmospheric Composition Change Model Intercomparison Project

The ACCMIP initiative was designed to facilitate the attribution of projected climate change to either internal climate sensitivity or differences in the radiative forcing. A fraction of the 23 models participating in the phase 3 of the Climate Model Intercomparison Project (CMIP) in support of the IPCC Fourth Assessment Report did include a representation of short lived climate forcers. Only about a third included black carbon and half of them accounted for future ozone changes. In addition, spatially variable radiative forcing was not stored in the CMIP3 archive. In order to fill this gap, and to improve the consistency in the model setup, the ACCMIP exercise was designed to complement the CMIP5 ensemble of global climate projections. This initiative is documented in a number of papers submitted in 2012 to a Special Issue[2] of Atmospheric Chemistry and Physics.

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[2] http://www.atmos-chem-phys-discuss.net/special_issue176.html

The evaluation of ozone trends over 1850-2100 in the ACCMIP ensemble is discussed in (Young et al., 2012). The mean tropospheric ozone burden is found to have increased by 29% between 1850 and 2000. This increase is largely compensated in the forthcoming century according to the most optimistic trajectory (RCP2.6) with a 22% decrease between 2000 and 2100. The other trajectories are less optimistic with a downward trend of 8 and 9% for the RCP4.5 and RCP6, respectively, and even project a further increase of 15% in the RCP8.5.

It is worth noting that the absolute spread amongst models is relatively low for both RCP2.6 and RCP8.5 in the 2100 projection because of the low emissions of NOx, CO and NMVOC. All models include a somewhat similar representation of the natural troposphere, where O3 is largely constrained by CH4, CO, NOx, and HOx, while they differ in their representation of the more complex VOC chemistry. That is why the signal is robust for the two most extreme scenarios, even though CH4 emissions are very high in the RCP8.5 (hence the climate signal and the increase of O3).

(Young et al., 2012) also address model validation for the historical period. They confirm the usual positive bias of global models over northern extratropics (largely due to their coarse resolution) even though they argue that the bias of the ensemble remains within the range of observed variability. The mean bias of ozone tropospheric column in the ensemble over the 30N-60N latitudinal band is 4.7 Dobson units (DU). This compares to 34.1DU observed by the OMI space borne instrument and a mean of the model ensemble of 38.8 DU with a standard deviation of 4.1 DU.

2.4.2 Boundary conditions used for the present assessment

Amongst the 15 ACCMIP models, the global chemistry climate model used in the present report is the LMDz-OR-INCA (Szopa et al., 2012) provided by courtesy of Sophie Szopa (from the Laboratoire des Sciences du Climat et de l'Environnement IPSL/CEA). The performance of that model falls at the centre of the spread of the ACCMIP ensemble with a bias of the tropospheric ozone column of 4.2DU over the 30N-60N latitudinal band (Young et al., 2012).

Ozone trends in the LMDz-OR-INCA model are also located in the centre of the envelope of the ensemble. In addition to the tropospheric column and trend, (Szopa et al., 2012) also provide the trend in surface ozone (**Figure 1**). They confirm the sharp downward trend in the RCP2.6 scenario and the increase in the most pessimistic RCP8.5. However the later increase is much more limited than reported for the total ozone burden that resulted from the increase of global methane which is more effective at increasing free tropospheric ozone than surface levels that are also affected by other sources.

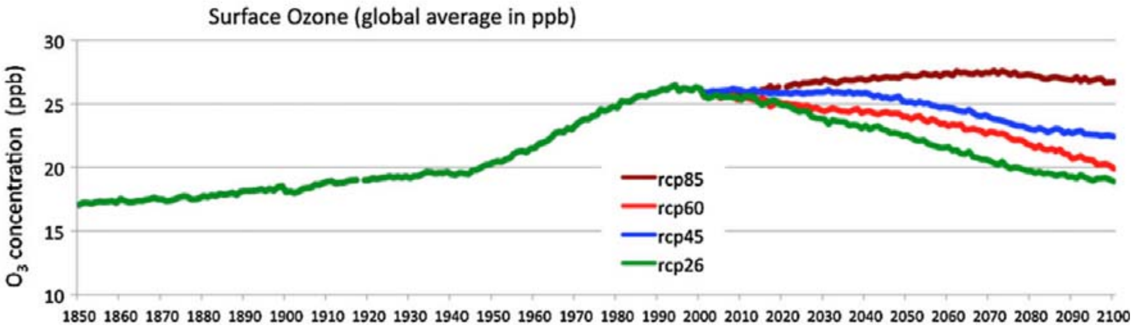


Figure 1: Evolution of surface ozone (ppbv) between 1850 and 2100 in the LMDz-OR-INCA simulation of the ACCMIP experiment according to the past emission trends (Lamarque et al., 2010), and future projections of the RCPs (van Vuuren et al., 2011). From (Szopa et al., 2012).

2.4.3 Sensitivity of the regional air quality model to the boundary conditions

According to (Schere et al., 2012; Szopa et al., 2009), the sensitivity of the regional air quality model to the prescribed boundary conditions is expected to be significant. The important projected changes in the background tropospheric chemistry documented in the ACCMIP exercise (Section 2.4.1) are thus expected to have a strong impact on the regional air quality in the CHIMERE simulations.

To assess the impact of the background we have performed sensitivity simulations by replicating a seasonal simulation over the summer 2003 using reanalysed meteorology and with varying chemical boundary conditions. For illustration purposes, Figure 2a shows the vertical profile above the Paris area which has been taken extracted from the global model being used as boundary conditions of the regional simulation. The monthly mean for the month of August in the control (2005) and the RCP2.6 and RCP8.5 for 2050 are displayed. In each case the monthly mean is an average over ten years centred on the given year. All profiles display a titration effect close to the surface. This titration effect occurs at night, and therefore bears upon the monthly mean. The remainder of the profile is in line with the projected evolution of ozone described in Section 2.4.1: decrease in 2050 in the RCP2.6 and slight increase in the RCP8.5 compared to the control (2005).

These global chemistry simulations have been used as boundary for three sensitivity CHIMERE runs, everything else (meteorology and regional emissions) being kept constant. In **Figure 2**b the monthly mean profile is given for the month of August 2003 in the Paris area. The ozone build-up resulting from the heat wave appears in the mid planetary boundary layer and lower troposphere although the titration effect still bears upon ozone levels at the surface. The three scenarios reflect the decrease in 2050 in the RCP2.6 and the increase in the RCP8.5, compared in both cases to the control case (2005) thereby illustrating the sensitivity of the regional model to the boundary conditions. Note that the RCP8.5 exhibits an additional ozone increment compared to the global model because it includes the effect of local emissions of precursors that build up as ozone in the regional model.

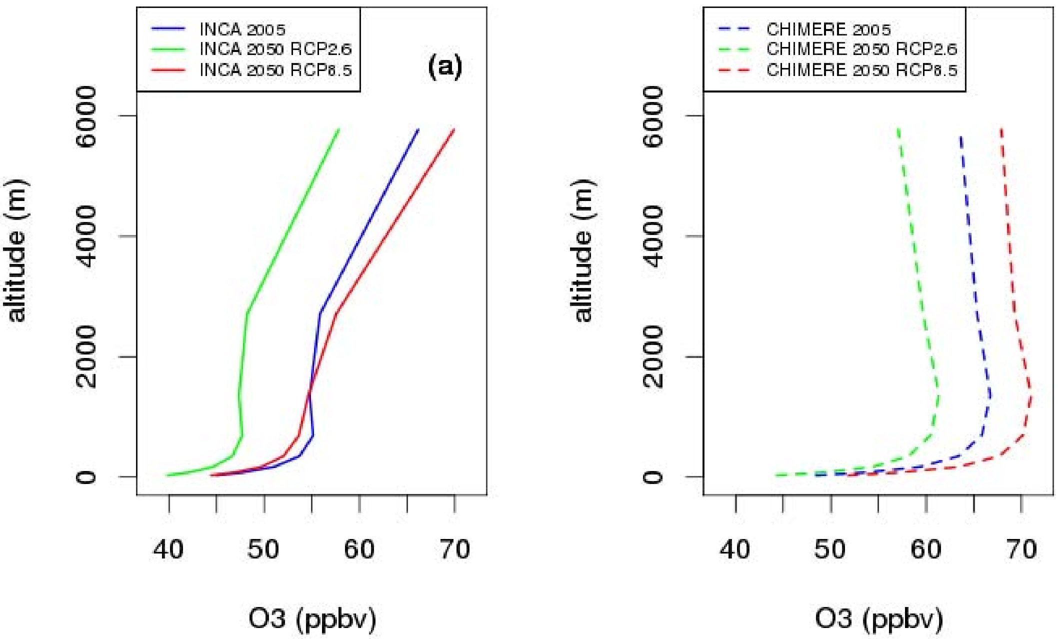


Figure 2: Vertical profiles of monthly mean ozone in the global model used as boundary condition (a) and in the regional CTM (b).

3 Air Quality and Climate Projections for 2050

3.1 Regional Air Quality and Climate Modelling System

The simulations used in the present assessment rely on the following suite of model and input data:

Scenarios and emissions:

A combination of IPCC and GEA data is used in the present study as it is considered to offer the best degree of refinement available to date. The vast majority of global modelling is currently performed on the basis of the IPCC RCPs, therefore we decided to use these widely distributed pathways for the climate and global chemistry modelling. For selected regions there are however better alternative offering a more explicit description of air quality policies (GEA, or the forthcoming HTAP emissions). As a consequence we decided not to use the RCP emission for regional air quality and rather implement the most recent available air pollutant emission projections.

Climate scenarios: The long lived greenhouse gases (CO2, CH4, N2O) pathways are the RCP2.6 and RCP8.5 prepared for the forthcoming AR5 of IPCC (van Vuuren et al., 2011). The corresponding emissions of short lived species are also used in the global chemistry model nudged within the climate runs.

Air quality scenarios: The chemically active anthropogenic pollutant and precursors (NOX, VOC, primary particulate matter, etc.) emission scenario of the Global Energy Assessment (GEA) (Riahi et al., 2012) were used over Europe in the regional air quality model since they offer a superior degree of representation of air quality policies over the RCPs, yet being consistent in terms of climate policy storylines.

Models:

Global climate: We use the IPSL-CM5 (Marti et al., 2010) coupled ocean-climate model simulations performed by CNRS/IPSL for the CMIP5 exercise. The highest resolution available for the required scenarios was used. As described by (Hourdin et al., 2012) this updated version offers a significant improvement over the low resolution version in terms of average temperature bias.

Global chemistry: The LMDz-OR-INCA (Szopa et al., 2012) coupled climate-biosphere-chemistry system nudged within the IPSL-CM5 climate fields was used to capture the atmospheric composition change.

Regional climate: The IPSL-CM5 fields were downscaled in a dynamical fashion with the WRF (Weather Research and Forecast (Skamarock et al., 2008)) mesoscale meteorological model. This initiative was performed as part of the CORDEX (coordinated regional climate modelling experiment) exercise (Giorgi et al., 2009).

Regional air quality: The Chimere (Bessagnet et al., 2008b) model was used driven by the regional climate field obtained with IPSL-CM5/WRF, using the boundary conditions of LMDz-OR-INCA, and the GEA emissions. The model has been involved in numerous model intercomparison exercises that demonstrated its capability to capture ozone and particulate matter concentrations (Colette et al., 2011; Cuvelier et al., 2007; Vautard et al., 2009; Vautard et al., 2006; Zyryanov et al., 2011; Pirovano et al., 2012).

An important added value of the setup lies in the use of the CMIP5 RCP greenhouse gases trajectories throughout the modelling setup (global climate, global chemistry, and regional climate) whereas the available literature (especially with regard to regional climate forcing) still relies on the previous generation CMIP3 data.

In addition, we use GEA air pollutant emission data over Europe that offer a refinement over the RCP with regard to their representation of European air quality policies.

Last, it should be mentioned that all the model simulation used here were performed by a consortium of INERIS and IPSL (Institut Pierre Simon Laplace) that are also the core developers of all the models used (atmosphere, biosphere, ocean, and chemistry) with the exception of the regional climate model.

As such, because of its high degree of consistency the present modelling suite deserves the title of Regional Air Quality and Climate modelling system. However it should be noted that with the exception of the global chemistry-climate, the models are not coupled, there is no interaction such as the impact of air pollution on climate (the radiative forcing discussed below is computed offline in a diagnostic model and has no effect on the climate fields used here). We also ignored any impact of pollution or climate on vegetation that could lead to a feedback loop through biogenic emissions of trace species.

3.2 Projected changes in air quality concentration

The results of the integrated air quality and climate simulations are displayed in **Figure 3**. For each scenario, the simulations include the effect of (1) global climate, (2) regional climate, (3) global chemical background, (4) regional air quality legislation.

Three scenarios are provided: a control (2005) corresponding to the present-day situation, and two projections for 2050, one of them (reference) assuming no implementation of any specific climate policy while the second (mitigation) aims at limiting global warming to 2K by the end of the century.

In each case, the regional air quality simulation covers 10 years in order to gain statistical significance and minimise the effect of climatic interannual variability.

Figure 3 displays the average concentrations for ozone, and total PM25 (including secondary aerosols), as well as sulphate (SO4p), nitrate (NO3p) and ammonium (NH4p) particles. For particulate matter, the annual mean is given while for ozone we provide the average of summer daily maxima. The difference in the lower two rows are given as projection minus the reference. Such differences are only plotted where found to be statistically significant with a student t-test at the 95% confidence level (the difference being reset to zero where un-significant). The results are discussed in the following paragraphs.

Ozone

The average summer maximum ozone field for the control (2005) simulation resembles the usual picture with a sharp latitudinal gradient with the exception of pollution hotspots over Europe. The ozone levels are however lower than reported with CHIMERE in similar exercises (e.g. (Colette et al., 2011; Colette et al., 2012a)) because of the cold bias of the forcing climate model being used here compared to the less biased meteorological reanalysis used before, hence supporting the findings of (Manders et al., 2012). Both projections for 2050 indicate a decrease of ozone, although this decrease is much more limited for the reference than for the mitigation case. Nevertheless it is interesting to point out the significance of the difference. Even if 10 year sequences are not considered to be long enough in terms of climate change assessment, it appears that the interannual variability of the modelled ozone projection is small enough to exhibit significant differences on a 10 year period.

PM2.5

The average fields of fine particles (PM2.5) in the control (2005) simulation also display local maxima over the air pollution hotspots beside the large influx at the southern boundary of the domain (desert dust). The decrease by 2050 is very large, with concentrations below 2µg/m3 over continental areas in both future scenarios. The magnitude of the change by 2050 is also very similar in the reference and mitigation projections, suggesting that the air quality legislation (identical in both scenarios) carries the bulk of the improvement for particulate matter. However, this statement deserves further investigation (see section 4) in order to discard any possible compensation between the driving factors (emissions, climate and boundary conditions).

Sulphate, Nitrate, Ammonium

Besides total particulate matter, secondary formed inorganic constituent require a dedicated investigation since they originate from distinct (here gaseous) precursors that do not follow the same mitigation trajectories.

The sulphate and nitrate fields for 2005 are very complementary, the former being higher over Eastern Europe while the second is high over the polluted Benelux, Germany, Southern UK and Northern Italy. For both of them the decrease is very pronounced by 2050, and similar for the two scenarios. The lack of decrease of NH3 emissions in the GEA projections (Colette et al., 2012b) is not reflected in the projected NH4p, emphasising the limiting role of NOx emissions through the availability of HNO3 in rural areas (Hamaoui-Laguel et al., 2012) that do exhibit a strong decrease in the future. As illustrated by these findings, the efficiency of NH3 mitigation on the reduction of ammonium nitrate pollution is related to very sensitive non-linear feedbacks and interactions. More definitive conclusions will be drawn from the upcoming work of the ETC on NH3 sensitivity scenario that will be conducted in 2013.

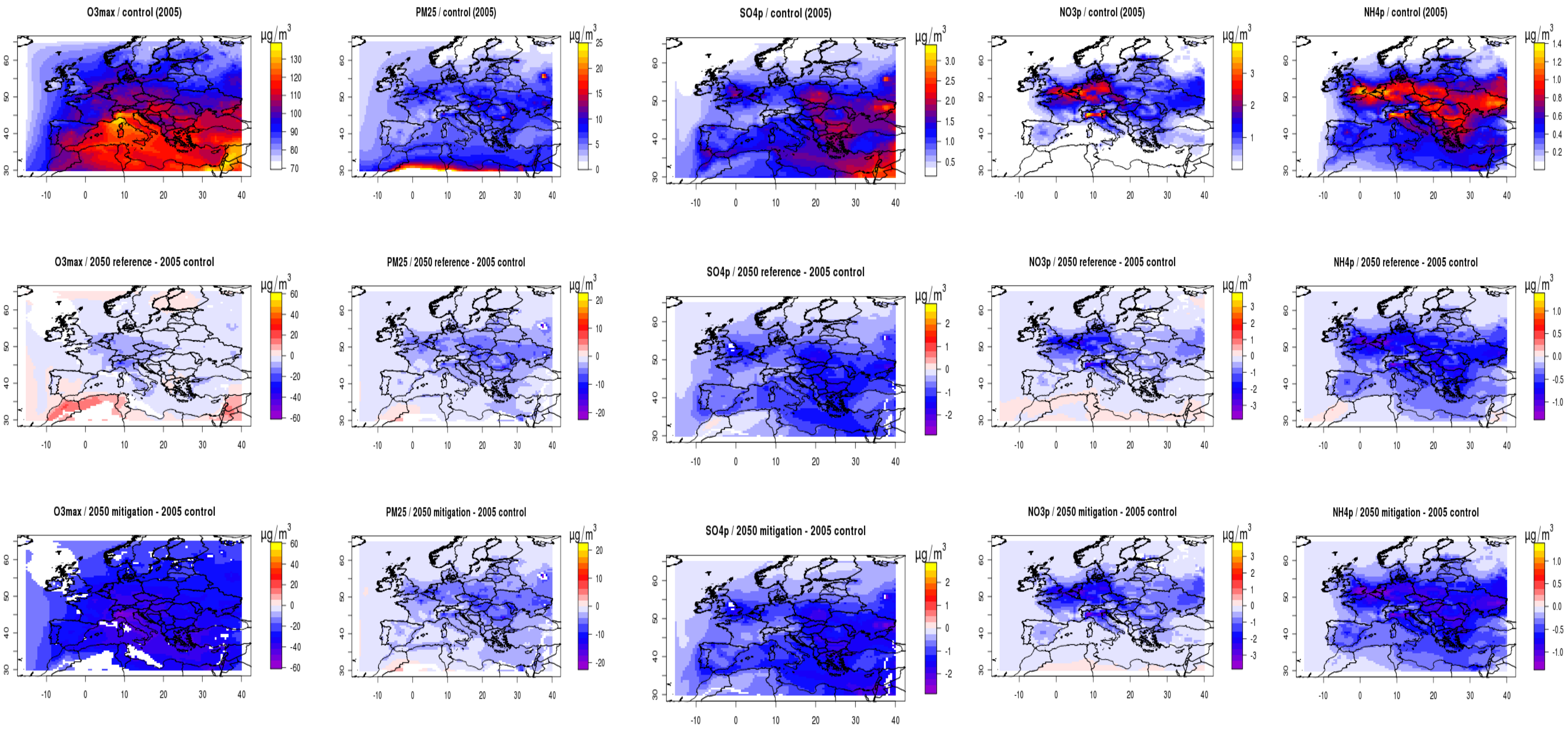


Figure 3: Top row (from left to right): average fields of O3 (summer daily max), PM2.5, SO4p, NO3p, NH4p (annual mean) in the control (2005) simulation (averaged over 10 years corresponding to the current climate). Following rows: difference between the simulations for 2050 and the control (2005) for the reference projection (middle row) and the mitigation case (lower row), the differences are only displayed where significant given the interannual variability of ten simulated years.

3.3 Projected changes in air quality exposition

Besides the projected evolution of the raw average concentration of air pollutant, assessing the projected change in detrimental exposure to air pollution for human health and vegetation requires investigating more relevant indicators (EEA, 2009).

3.3.1 Exposure to ozone

In **Figure 4** we display the average SOMO35 and AOT40 for the control simulation as well as the projected changes. These two indicators are respectively relevant for human health and impact on crops. They are defined as:

- SOMO35: the annual sum of daily maximum over 35ppbv (based on 8-hr running means), expressed in µg/m3.
- AOT40c: accumulated ozone over 40ppbv from 8am to 8pm over May to July, expressed in µg/m3.hr and based on hourly data.

At first order, the average fields of SOMO35 and AOT40 follow the pattern of the average summertime ozone daily maximum displayed in **Figure 3**. The projected change is however very different.

SOMO35 tends to increase in the reference case while AOT40 decreases (these two trends being very limited). The slight decreases under that scenario are limited to central part of the domain whereas Spain is exposed at best to a stagnation of ozone levels, and significant increase are found over North Africa.

The mitigation scenario achieves a much higher degree of emission reduction with a limited global warming as well as a decrease of the global ozone burden. As a result both SOMO35 and AOT40 decrease sharply, especially in the Mediterranean area where the levels were highest. As opposed to the reference, in the mitigation scenario (that resembles the RCP2.6 in terms of climate policy), the downward trend is more pronounced for SOMO35 than for AOT40. This finding illustrates again the high non-linearity of proxies used to depict the exposure to detrimental exposure to ozone. It also emphasises the sensitivity of the results. Whereas all the findings discussed here are statistically significant, the robustness of such limited trends would benefit from an ensemble approach rather than relying on a single model realisation.

On a more quantitative basis in order to emphasize the projected changes in high-exposure areas, we apply weighting functions to the SOMO35 and AOT40c fields. These weighting functions are either the population density (for SOMO35) or the fraction of crops in the landuse (for AOT40c). We find very different trends for the exposure of both population and vegetation. The population-weighted SOMO35 increases by 9.7% in the reference scenario whereas it decreases by 77.9% in the mitigation case. The crops-weighted AOT40 decreases by 8.9% and 94.9% in the reference and mitigation scenarios, respectively. The difference in the net projected change in terms of (1) average daily maximum ozone, (2) SOMO35, (3) AOT40 is a direct consequence of the high non-linearity of ozone chemistry where a given change in the emitted precursor, or in the climate conditions can have different impact on the peaks (1), the peaks over a threshold (2), or the background over a threshold (3). This sensitivity argues for the implementation of full frame chemistry-transport models as being done here rather than simplistic extrapolation of possible ozone changes as a result of global temperature changes.

3.3.2 Exposure to particulate matter

For particulate matter, the most relevant exposure indicator remains the annual average PM25 displayed in **Figure 3**.

We find that population-weighted PM25 decreases by 39.8% and 47.9% in the reference and mitigation scenarios, respectively. As mentioned above, it appears that air quality legislation (that is identical in both scenarios) somewhat dominates the relative change in exposure to PM25, the impact of the climate policy (that differs in both scenarios) is not a large as observed for the exposure to ozone.

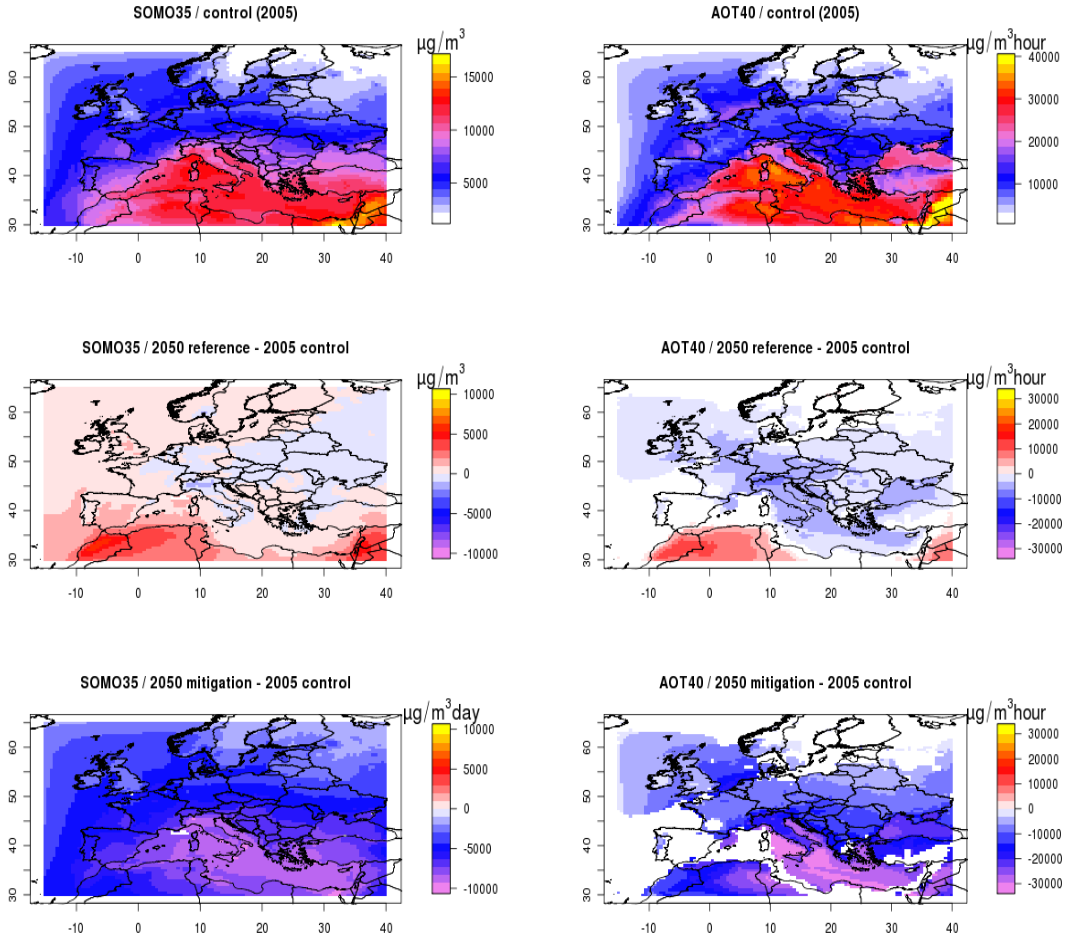


Figure 4: Top row (from left to right): average fields of SOMO 35 (µg/m3 day) and AOT40 for crops (µg/m3 hour) in the control (2005) simulation (averaged over 10 years corresponding to the current climate). Following rows: difference between the simulations for 2050 and the control (2005) for the reference projection (middle row) and the mitigation case (lower row), the differences are only displayed where significant given the interannual variability of ten simulated years.

3.4 Projected changes in radiative forcing

The projected impact of air quality on climate is analysed using the aerosol radiative forcing in the CHIMERE results. An offline post-processing optical model is used to infer the aerosol optical thickness (AOT), single scattering albedo (SSA) and asymmetry parameter from the aerosol concentration, size, and chemical composition in the CHIMERE simulations (Péré et al., 2010). These quantities are then provided to a radiative transfer code which handles absorption processes with a line by line code and scattering with the discrete ordinate method (GAME, (Dubuisson et al., 2006)) to obtain the total atmospheric direct radiative forcing.

We only discuss the radiative forcing attributed to aerosol in this report since it constitutes the dominating factor of variability in the lower troposphere covered by the regional air quality model. Rayleigh scattering and absorption by major gaseous species such as water vapor, carbon dioxide, methane and ozone are taken into account by using climatological profiles. Even ozone variability is ignored considering that for that constituent most of the interaction with incoming solar radiation occurs in the upper-troposphere and the lower-stratosphere (where O3 concentrations are high and UV radiation abundant).

Note that this forcing includes only the direct interaction of aerosol with light, and ignores any indirect effects such as the modification of cloud properties. Unlike results discussed in Section 3.2 and 3.3, the radiative forcing estimates are derived from 5 years out of the 10 simulated for each scenario (for computational cost and storage efficiency considerations).

The current aerosol direct forcing at the top of the atmosphere (TOA) is displayed in **Figure 5**, together with the projected change by 2050 in the reference and mitigation scenarios. We confirm the net cooling effect of about -1W/m2 in the current atmosphere above Europe. The global mean present-day aerosol radiative forcing in the latest estimate of the ACCMIP project (Shindell et al., 2012) is -0.26W/m2 on average for 10 global models but the composite over the ensemble indicates a radiative forcing of about -0.9W/m2 over Europe which is in line with our estimate.

The projections for 2050 using the CHIMERE model point towards an increase of the radiative forcing that becomes closer to zero since its absolute magnitude decreases as a result of lower concentration of PM25 in the atmosphere. The relative warming effect appears to be very similar for both scenario that exhibit similar trends of PM25, as mentioned above.

Similar results are found for the vast majority of models participating in the recent radiative forcing assessment performed in the framework of the ACCMIP exercise (Shindell et al., 2012).

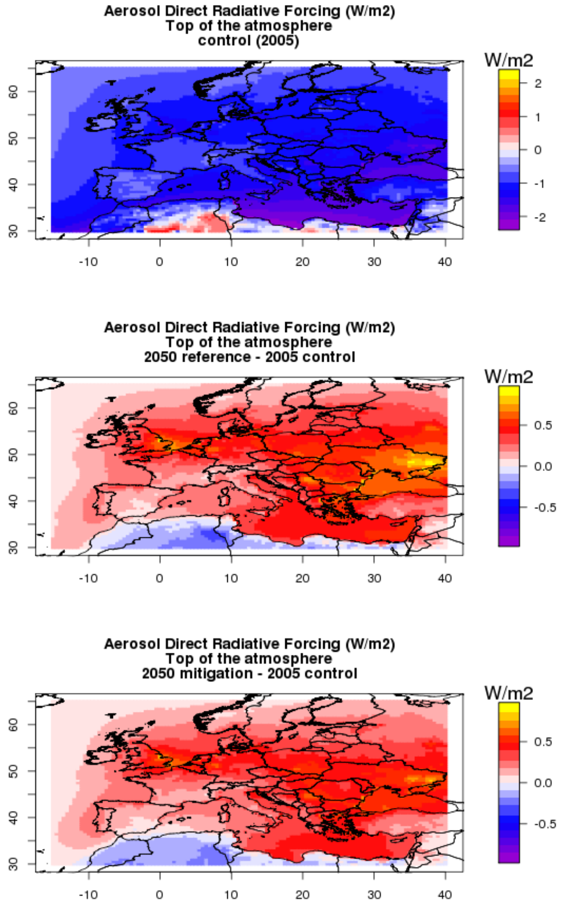


Figure 5: Top: average fields of the aerosol direct radiative forcing at the top of the atmosphere (W/m2) in the control (2005) simulation (averaged over 5 years corresponding to the current climate). Following rows: difference between the simulations for 2050 and the control (2005) for the reference projection (middle row) and the mitigation case (lower row).

4 Attribution of the driving factor

The projected exposure to air pollution discussed in Section 3 takes into account the whole range of processes playing a role in the future evolution of air quality. The Regional Air Quality and Climate Modelling System captures projected changes in global and regional climate, the role of chemical background changes as well as local air quality mitigation measures.

This simulation dataset offers thus a unique opportunity to investigate the respective role of each driving process. This section is devoted to the investigation of a methodology to quantify the individual impact of climate, long range transport and regional measures to the projected air quality by 2050. This methodology is introduced and implemented on the basis of short model sensitivity experiment. Preliminary findings are introduced to illustrate the scope of this new indicator, however these findings should be considered with care and will be strengthened in the future by means of longer sensitivity experiment and/or ensemble approaches.

4.1 Methodology

We proceed to a number of sensitivity scenarios in order to isolate the impact of each driving factor. By replicating the simulations with all things kept equal except one of the driving factor one shall quantify the respective role of each process.

However because of computational constrains, it is not possible to duplicate the decadal simulation for each possible combination of factors. Therefore for the sensitivity studies aiming at isolating the impact of emission or boundary conditions, we used simulations over one season. Using a 10-yr reanalysis of the past decade, we could identify the most relevant seasons to investigate significant summer time ozone and springtime particulate matter events. For O3, we selected the summer 2006 (2003 being much too outstanding) but we also duplicated the experiment with an unfavourable year (1998) for checking purposes. For PM2.5 we chose to focus on springtime 2003. These sensitivity simulations are now being extended to annual periods in order to gain in statistical significance.

Such seasonal sensitivity studies can be used to infer the role of boundary conditions or projected emission changes because they lack any interannual variability. On the contrary, climate is highly variable from year to year. The role of climate was thus derived by withdrawing the contribution of boundary conditions and emission from the simulations discussed in Section 3 that include all the factors.

It should be noted however that the present assessment would gain in robustness if the sensitivity simulations were performed on an annual or even multi-annual basis. In addition, these results are very model dependant, and an ensemble of complementary numerical tools should be sought after in the future to reduce the uncertainty of the finding reported here.

4.2 Results

In order to illustrate the scope of a quantitative integrated indicator on the impact of climate on air quality, we introduce here the preliminary findings obtained when implementing the methodology outlined in Section 4.1 on short model sensitivity experiments. The results might change substantively using a different model, or longer sensitivity tests.

The bar-chart of **Figure 6** provides the relative change of PM25 and daily maximum O3 that can be attributed to each of the three driving factors: the chemical boundary conditions (background long range transport), the European emissions, and meteorological conditions which are affected by climate change. These bar-charts are produced for an average over Western Europe (5W, 15E, 40N, 55N) while the corresponding maps for the whole region are given in **Figure 7**.

Ozone

We find that in all cases, the projected change in emissions dominates over the other factors. Recent studies on ozone projections relying on air pollutant emissions prescribed by the RCPs also reported that anthropogenic emission changes dominate over the effect of climate (Katragkou et al., 2011; Langner et al., 2012; Manders et al., 2012). The fact that we use very different air pollutant emission projection (we rely on GEA for the air pollutant and RCP for the long lived greenhouse gases, whereas previous work use RCPs for the whole atmospheric system) adds robustness to this statement.

Climate change is found to represent a penalty with regards to the future evolution of ozone. In both climate projections (RCP2.6 and 8.5) temperature increases in the future, even if this increase is limited for the RCP2.6. A more surprising feature is the fact that the climate penalty is lower for the RCP8.5 than for the RCP2.6. The maps of **Figure 7** confirm that this penalty is lower over continental areas and climate even appears as a net benefit for O3 levels over the North Sea. A closer look at the total precipitation shows a significant change in the projection suggesting a modification of the weather regimes (frequency of stagnation episodes such as heat waves, frequency of low-pressure systems, large scale climate oscillations, displacement of the storm-track, etc.). We conclude that we cannot confine the role of climate change on ozone pollution to the projected change in summertime temperature only, but rather the whole climate system, including weather regimes, must be taken into account thereby illustrating the relevance of our indicator that integrates all the component of the climate system as opposed to individual indicators (EEA, 2004b).

The contribution of the background, long range transport, is also worth pointing out since it appears to carry a penalty for the reference case (RCP8.5) while a benefit is found for the RCP2.6. This behaviour was expected given the trends in the global ACCMIP projections discussed in Section 2.4.

Particulate matter

The PM25 climate and chemistry projection constitute an original feature of the present assessment as most of the existing literature in regional projection is limited to ozone.

Similarly to ozone, we find that anthropogenic emissions dominate the projected change.

The background appears to play a smaller role than for ozone which was expected given the shorter lifetime of most particulate species. However, this contribution is not negligible for the mitigation scenario. By looking at the corresponding figures for each individual PM compound we found that this decrease is attributable to decreases across the whole range of PM compounds (sulphate, nitrate, ammonium, black and organic carbon) that is not compensated by the limited increase in dust influx that is slightly larger in the mitigation than in the reference scenario because of different atmospheric circulation patterns.

One of the key results of this investigation regards the impact of climate on PM2.5. Note that we refer in this paragraph to the geophysical impact of climate change, whereas the impact of climate mitigation measures on PM2.5 was found to be limited in Section 3.2. In these preliminary results, the magnitude of the contribution of climate change is larger for PM2.5 than for ozone which opens large research perspectives given that the vast majority of the literature on regional air quality and climate is limited to ozone. Furthermore climate change is found to constitute a penalty in the mitigation and a benefit in the reference. This beneficial impact for particulate air pollution of dangerous climate change under the most pessimistic RCP8.5 surely deserves further investigation. The analysis of the projection of individual climate variables shows that the downward trend of PM2.5 in the pessimistic climate scenario is due to the higher temperatures that inhibit the formation of ammonium nitrate. Ammonium nitrate constitute a significant fraction of the secondary inorganic aerosol that build up during springtime stagnation episodes. Under satisfactory environmental conditions, they shall be produced from nitrogen and ammonia precursors. The higher temperature under the RCP8.5 will probably act against the formation of NH4NO3p because of its formation pathway.

This climate benefit for future PM25 is found to apply for most continental Europe, whereas a penalty is found over the sea surfaces (increased sea salt) and at the southern boundary (desert dust influx) in the reference case.

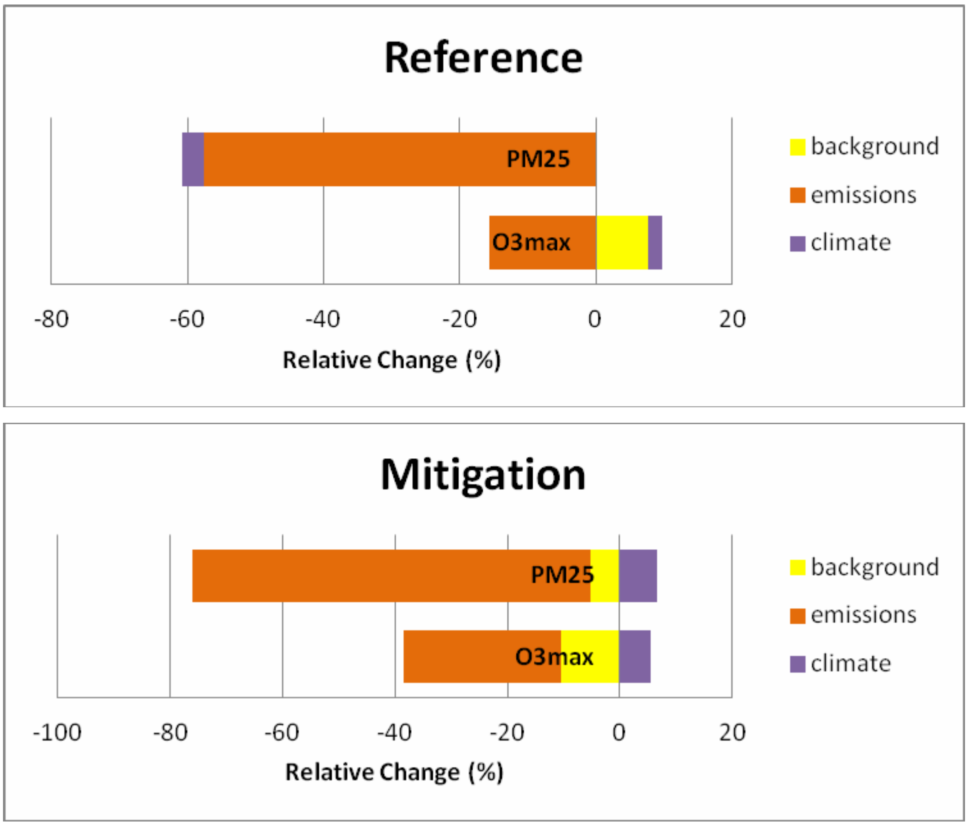
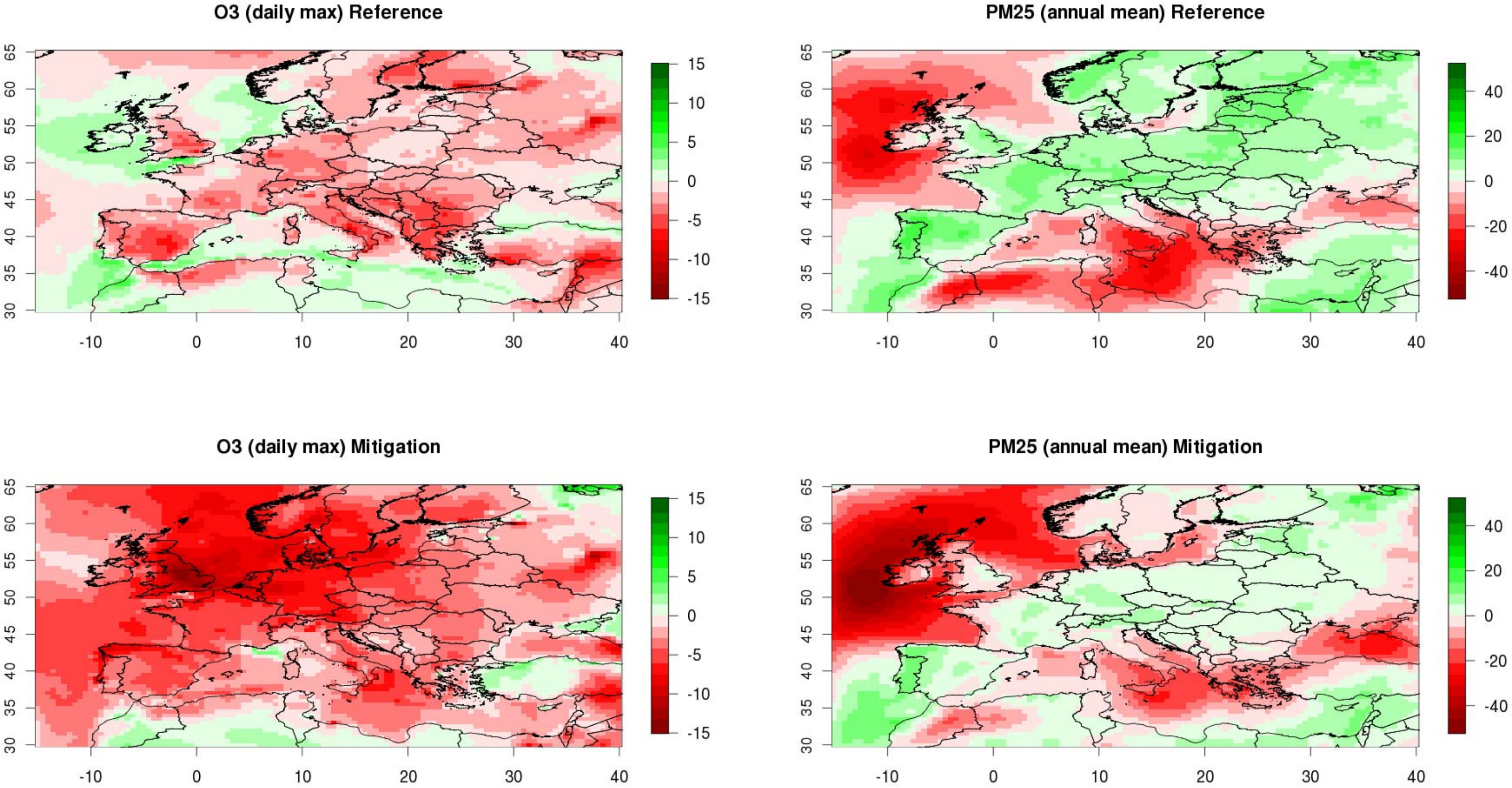


Figure 6: Relative contribution of the background air pollution, regional emissions, and climate change to the projected changes in PM25, and O3 concentration averaged over Western Europe in 2050 according to the reference (top) and mitigation (bottom) scenarios.



O3 (daily max) Reference

PM25 (annual mean) Reference

O3 (daily max) Mitigation

PM25 (annual mean) Mitigation

Figure 7: Map of the relative contribution (in %) of the regional climate to the projected change in air quality (average summertime daily maximum of ozone, left, and annual mean PM25, right) for the reference (top) and mitigation (bottom) scenarios. A negative sign (red) indicates a climate penalty, whereas a positive sign (green) shows that future climate tends to minimize detrimental air pollution levels.

5 Conclusion

Low carbon scenarios at the 2050 horizon are investigated with a regional air quality and climate modelling system. Future anthropogenic emission scenarios tailored to mitigate climate impacts and limit global warming to 2K by the end of the century have consequences for air pollution as well. Air quality is also sensitive to external factors such as long range transport determining the influx of air pollutants in Europe, and global and regional climate change. Acknowledging the multiplicity of interlinkages, a comprehensive modelling system was designed building upon state-of-the-art numerical tools and recent underlying emission projections. The present report offers an overview of existing emission projections, a focus on the main externalities such as regional climate modelling and chemical boundary conditions, and a detailed presentation of the results of a dedicated modelling experiment that includes a section on the attribution of the projected change to the main driving factors.

The assessment relies on an optimal combination of the latest source of emission data. The Representative Concentration Pathways prepared for the forthcoming Fifth Assessment Report of IPCC are used for the global climate and chemistry simulations. The air pollutant emission used for the regional air quality simulations are those of the more recent Global Energy Assessment that constitute a refinement over the RCPs since they includes emission factors representative of the current legislation in Europe.

At all scales of the climate and chemistry system, the results presented here build upon a suite model simulations produced in the framework of well established international coordinated experiments. The coupled atmosphere - ocean global climate simulations are those of the next phase of the Climate Modelling Intercomparison Project. The global climate-chemistry simulations (that prescribe background chemical changes) are those of the Atmospheric Composition Change Model Intercomparison Project. The regional climate projections are produced in the context of the CORDEX dynamical downscaling coordinated experiment. A specific focus on the global chemistry and regional climate components of the modelling chain is discussed in the report.

The results of the regional air quality and climate modelling system are detailed with a particular focus on indicators describing impacts on health and vegetation. Our analysis pays attention to the attribution of various factors (emission changes in Europe, changes of influx of air pollutants and climate change) to the total projected changes of air quality.

We have found that climate policies have a limited impact on PM2.5 levels that already decrease sharply under all scenarios because of current air quality policies. This decrease in PM2.5 levels will lead to a reduction of a factor two of the magnitude of the net cooling effect of the radiative forcing of pollution aerosols.

The projection for ozone is more complex: in the mitigation scenario exposure of population (SOMO35) and crops (AOT40) to detrimental ozone concentration decreases by 78% and 95%, respectively. However, for the reference scenario, an increase of SOMO35 of 10% is found by 2050, whereas AOT40 decreases by 9%. Even though both scenarios include the same air quality legislation over Europe, the reference scenario suffers from the absence of energy efficiency measures, therefore affecting global and regional climate as well as the chemical background.

Using sensitivity simulations, it was possible to de-convolute the relative contribution of European emissions, long range transport (influx of air pollution in Europe) and climate change to the total projected change. We propose a methodology to compute the penalty (or the benefit) of climate change for air pollution. Starting from a comprehensive simulation including all factors (on a statistically significant number of years), and withdrawing the contribution of emission and boundary conditions (with sensitivity simulations), we could quantify an integrated contribution of climate that combines several processes, going beyond simplistic assessments based for example on the overall increase of temperature under projected climate change. The scope of such an integrated indicator of the net impact of climate on air quality is illustrated by introducing preliminary results obtained with relatively short sensitivity tests.

The well documented penalty brought about by climate change on ozone is confirmed even though, more surprisingly, it is found to be more limited in magnitude in the most pessimistic climate scenario (RCP8.5) compared to the RCP2.6. Even though the global temperature increase is larger with the RCP8.5 it is accompanied by changes in weather regimes that diminish the occurrence of ozone pollution events. Long range transport is found to constitute a penalty in the reference case (as global tropospheric ozone increases in this case), whereas the contribution from the background decreases by 2050 under the mitigation pathway (with global tropospheric ozone levels decreasing in this case).

A key finding in these preliminary results is that the effect of climate change to the projected change of air pollution levels is as important for PM2.5 as for ozone. We also found that climate change slightly deteriorates PM2.5 levels the mitigation pathway, whereas it slightly further improves PM2.5 levels the reference case.

The present report introduce a new integrated indicator of the impact of climate change on air quality that can be used to assess the penalty or benefit brought about by climate change on given air pollutants. This indicator can be presented as aggregated values over a given domain, or as maps. It allows to discuss competing impacts of climate change for ozone exposure impact indicators and for particulate matter that are not discussed in existing literature on regional air quality and climate projections. However the sensitivity of these results to the duration of the sensitivity tests and the model implemented should be investigated further in the future by performing such analyses with an ensemble of models, and using longer time periods for the sensitivity simulations.

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