

This discussion paper is/has been under review for the journal Atmospheric Chemistry and Physics (ACP). Please refer to the corresponding final paper in ACP if available.

# European atmosphere in 2050, a regional air quality and climate perspective under CMIP5 scenarios

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Received: 28 January 2013 – Accepted: 26 February 2013 – Published: 11 March 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

**ACPD**

13, 6455–6499, 2013

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## Abstract

To quantify changes in air pollution in Europe at the 2050 horizon, we designed a comprehensive modelling system that captures the external factors considered to be most relevant and relies on up-to-date and consistent sets of air pollution and climate policy scenarios. Global and regional climate as well as global chemistry simulations are based on the recent Representative Concentrations Pathways (RCP) produced for the Fifth Assessment Report (AR5) of IPCC whereas regional air quality modelling is based on the updated emissions scenarios produced in the framework of the Global Energy Assessment. We explored two diverse scenarios: a reference scenario where climate policies are absent and a mitigation scenario which limits global temperature rise to within 2 °C by the end of this century.

This first assessment of projected air quality and climate at the regional scale based on CMIP5 (5th Climate Model Intercomparison Project) climate simulations is in line with the existing literature using CMIP3. The discrepancy between air quality simulations obtained with a climate model or with meteorological reanalyses is pointed out. Sensitivity simulations show that the main factor driving future air quality projections is air pollutant emissions, rather than climate change or long range transport. Whereas the well documented “climate penalty” bearing upon ozone over Europe is confirmed, other features appear less robust compared to the literature: such as the impact of climate on PM<sub>2.5</sub>. The quantitative disentangling of each contributing factor shows that the magnitude of the ozone climate penalty has been overstated in the past while on the contrary the contribution of the global ozone burden is overlooked in the literature.

## 1 Introduction

Air quality and climate are closely inter-related in their mitigation, their functioning, and their impacts (Jacob and Winner, 2009). Climate policies imply energy efficiency and other technical measures that have an impact on a wide range of human activities and,

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in turn, on air quality. Reciprocally, air quality mitigation measures may also have an impact on greenhouse gases emissions. In addition, air quality is sensitive to climate change (which affects physical and chemical properties of the atmosphere and therefore drives the frequency of weather events yielding favourable conditions to the build up of pollution). Last, many air pollutants (both gaseous and particulate) have direct and indirect impacts on climate through the radiative balance of the atmosphere.

The combined and sometimes competing role of these interlinkages calls for integrated assessment frameworks (EEA, 2004). Integration of technical mitigation measures, their costs and their impact on air quality have been successfully implemented over the past decades to investigate relatively short time periods (Cohan and Nape-lenok, 2011). In Europe, the GAINS (Greenhouse Gas–Air Pollution Interactions and Synergies) modelling framework (Amann et al., 2011; Amann and Lutz, 2000) is used extensively to support the design of cost-effective emission reduction strategies. 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) designed to explore the impact on air quality of incremental changes in European emissions over the next couple of decades. However the robustness of these optimisation tools for longer term projections is challenged by externalities such as the global burden of pollution and the climate penalty (Wu et al., 2008).

Full frame atmospheric chemistry and climate models can contribute to better quantifying these externalities. The most established approach to tackle such issues consists in relying on ensemble of models exploring a range of likely futures in order to derive an envelope of projections, as being done in the widely documented IPCC framework (IPCC, 2007). When it comes to atmospheric chemistry there is still a gap between research communities working on global and regional scales. Global chemistry-transport modelling teams are closely aligned with the climate modelling intercomparison project (CMIP) (Taylor et al., 2012). A dedicated atmospheric composition change model inter-comparison project (ACCMIP) (Lamarque et al., 2012) was recently tailored to produce a consistent envelope of atmospheric composition projections accounting for climate

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impacts. Such global modelling initiatives often include sophisticated handling of coupling and feedbacks (esp. with regards to the radiative impact of short-lived climate forcers, Shindell et al., 2012). However they suffer of a lack of refinement over given regional areas and many of these tools include simplified formulation of chemical processes, especially with regards to secondary aerosol formation.

Regional air quality and climate modelling systems can fill these knowledge gaps. However, robust quantification of regional AQ externalities is still suffering from a lack of coordinated multi-model initiatives that would cover the whole range of processes involved. Over the past few years, there has been a growing body of literature on the ozone climate penalty over Europe (Andersson and Engardt, 2010; Hedegaard et al., 2008, 2012; Katragkou et al., 2011; Langner et al., 2012a,b; Manders et al., 2012; Meleux et al., 2007), amongst which only (Langner et al., 2012b) offers a multi-model perspective. This climate penalty is however rarely compared to other influential factors whereas the latest evidences suggested that reductions in air pollutant emissions would largely compensate the climate penalty (Hedegaard et al., 2012; Langner et al., 2012a). The role of long range transport is also somewhat overlooked in the literature apart from the sensitivity studies of (Langner et al., 2012a) and the assessment of (Szopa et al., 2006). It should also be noted that the vast majority of the regional air quality literature is devoted to ozone with very few studies focusing on particulate matter (Hedegaard et al., 2012; Manders et al., 2012).

We intend to quantify the penalty/benefit brought about by the externalities constituted by climate change and global pollution burden bearing upon ozone and particulate pollution over Europe. Four models are involved: a coupled ocean-atmosphere global circulation model (AOGCM), a global chemistry transport model (GCTM), a regional climate model (RCM) and a regional chemistry transport model (RCTM). Based on this approach, we can cover global and regional scales for both transport and chemistry.

For the global climate and chemistry modelling, we use the Representative Concentrations Pathways scenarios (van Vuuren et al., 2011) developed for the CMIP5 project

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(Taylor et al., 2012). While the RCPs also include detailed estimates of chemically active anthropogenic pollutants and precursors, the scenarios were designed solely with respect to long-term radiative forcing and each developed by different integrated assessment models. Hence they do not provide consistent scenarios to analyse climate and air pollution policy interactions (see also Butler et al., 2012; Fiore et al., 2012, for discussion). Given our goal of looking closer at regional air quality issues, we selected air pollution scenarios from the more recent Global Energy Assessment (GEA<sup>1</sup>) (Riahi et al., 2012). The GEA scenarios while being consistent with the RCPs – identical long-term radiative forcing levels – also include a detailed representation of air quality policies. To our knowledge, this study is the first to address future air quality over Europe under the hypotheses of the recent Representative Concentration Pathways (RCP) whereas there are a number of global or hemispheric assessments (Hedegaard et al., 2012; Shindell et al., 2012; Young et al., 2012).

This paper is structured as follows. Section 2 describes the chosen emission scenarios for greenhouse gases and chemically active pollutants. The models constituting the regional climate and air quality modelling system are presented in Sect. 3. The modelling results are discussed in Sect. 4.1 for the regional climate projection and Sect. 4.2 for the air quality projection. The sensitivity simulations designed to quantify the respective contribution of climate, long range transport and regional air pollutant emission changes is conducted in Sect. 4.3.

## 2 Emission scenarios

We use the RCP8.5 and RCP2.6 climate scenarios from the CMIP5 set that cover the highest and lowest ranges in terms of radiative forcing explored by the RCP scenarios. The corresponding emissions of short lived species are used in the global chemistry model that will be used to constrain the regional air quality model at its boundaries.

<sup>1</sup>[http://www.iiasa.ac.at/Research/ENE/GEA/index\\_gea.html](http://www.iiasa.ac.at/Research/ENE/GEA/index_gea.html)

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The RCP2.6 is designed to keep global warming below 2 °C by the end of the century whereas RCP8.5 does not include any specific climate mitigation policy and thus leads to a high radiative forcing of 8.5 Wm<sup>-2</sup> by 2100. We focused on the two scenarios from the GEA set that include an identical representation of all current air quality legislation in Europe but differ in terms of policies on climate change and energy access. The Reference scenario (also called CLE1) assumes no specific climate policy and has a climate response almost identical to the RCP8.5 while the mitigation scenario (CLE2) includes climate policies leading to a stabilisation of global warming (hence resembling the RCP2.6). These scenarios are based on modelling with MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) for the energy system (Messner and Strubegger, 1995; Riahi et al., 2007). MESSAGE distinguishes 11 world regions, including Western Europe and Central and Eastern Europe<sup>2</sup>. The emissions (CH<sub>4</sub>, SO<sub>2</sub>, NO<sub>x</sub> (nitrogen oxides), CO, NMVOC (non-methane volatile organic compounds), Black and Organic Carbon, PPM (fine primary particulate matter)) are subsequently spatialised on a 0.5 degree geographical grid using ACCMIP emission data for the year 2000 (Lamarque et al., 2010). Further details of the GEA air pollution modelling framework are available in (Rao et al., 2012).

The main strength of the GEA scenarios lies in the use of an explicit representation of all currently legislated air quality policies until 2030 based on detailed information from the GAINS model (Amann et al., 2011). For OECD Countries in particular, this includes a wide variety of pollution measures including Directives on the sulphur content in liquid fuels, emission controls for vehicles and off-road sources up to the EURO-IV/EURO-V standards; emission standards for new combustion plants and emission ceilings as well as the revised MARPOL VI legislations for international shipping. The inclusion of detailed AQ policies in the 2005–2030 period has a significant impact on the emissions of pollutants in the GEA scenarios so that, compared to the RCPs, larger co-benefits of climate policies for air pollution can be expected as detailed in Colette

<sup>2</sup><http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE-model-regions.en.html>

et al. (2012b). After 2030, the GEA scenarios implicitly assume through decline in emission factors, continued air quality legislation given a defined level of economic growth. Further details are provided in Riahi et al. (2012).

The total emissions of the main anthropogenic pollutants or precursors thereof are given in Table 1. The Reference or CLE1 scenario in absence of climate policy already shows a decline by 2050 of about 35–45 % (depending on the constituent) of the current level of emissions emphasizing the efficiency of current legislation with regards to air pollutant emissions in Europe. The decrease is even larger when climate policy is implemented as in the CLE2 scenario. NO<sub>x</sub> and VOC decrease to 14–22 % of current level, indicating a 50 % co-benefit of climate policy for air quality.

Using this combination of RCP and GEA scenarios offers the possibility to take into account explicit AQ policies that were not the scope of the RCPs. The only shortcoming of this option regards the inconsistency of chemically active emissions used in the global and regional models, given that the first prescribes boundary conditions of the second. A higher consistency could be achieved either by using GEA data to drive the global models or RCPs to drive the regional AQ model. The first option was ruled out because we preferred to use existing simulations of well established international model intercomparison projects. The second option would have led to ignore the added value of the consistent representation of air quality policies in the GEA pathways (Butler et al., 2012; Colette et al., 2012a,b; Fiore et al., 2012).

### 3 Modelling framework

The present assessment builds upon a suite of models covering various compartments of the atmospheric system. A global coupled atmosphere–ocean general circulation model and a global chemistry transport model address projected climate change and its impact on global chemistry. The global climate and chemistry fields are then down-scaled with regional models. The individual tools of this modelling suite are briefly described here.

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### 3.1 Global circulation model

The large scale atmosphere–ocean global circulation model (AOGCM) is the IPSL-CM5A-MR (Institut Pierre Simon Laplace Coupled Model) (Dufresne et al., 2013; Marti et al., 2010). It includes the LMDz meteorological model (Hourdin et al., 2006), the OR-CHIDEE land surface model (Krinner et al., 2005), the oceanic NEMO model (Madec et al., 1997) and the LIM sea-ice model (Fichefet and Morales-Maqueda, 1999). The external forcing in terms of anthropogenic radiative forcing is prescribed by the RCPs (Sect. 2). The medium-resolution version of the model is used ( $2.5 \times 1.25$  degrees in the horizontal and 39 vertical levels).

Switching the meteorological forcing from reanalyses to a climate model is a prerequisite to explore future projections. The difference between the two settings is that the climate model attempts to capture a climate that is representative of present conditions, whereas the reanalysis consists in the actual realisation of the past few years. Considering that significant impact on air quality projections have been reported before (Katragkou et al., 2011; Manders et al., 2012; Menut et al., 2012; Zanis et al., 2011), we decided to investigate here both a historical scenario (based on the climate model) and a hindcast (using the ERA-interim reanalyses, Dee et al., 2011).

### 3.2 Regional climate model

The Weather Research and Forecasting (Skamarock et al., 2008) (version 3.3.1) mesoscale model is used as a regional climate model (RCM) for the dynamical downscaling of the IPSL-CM5A-MR global fields. The spatial resolution is 50 km and the domain covers the whole of Europe with  $119 \times 116$  grid points. The setup of the RCM is the same as that of (Menut et al., 2012) which presents a detailed evaluation of the performances of the IPSL-CM5-LR/WRF regional climate modelling suite for air quality modelling purpose. However, we use here an updated, higher resolution version of the AOGCM (IPSL-CM5A-MR) which exhibits a smaller cold bias over the North Atlantic (Hourdin et al., 2012). A somewhat similar setup is used for the IPSL-INERIS

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contribution (Vautard et al., 2013) to the forthcoming Coordinated Regional Climate Modelling Experiment (CORDEX, Giorgi et al., 2009). The main differences compared to (Vautard et al., 2013) include: using 11 yr time slices instead of transient simulations, a slight spectral nudging in the upper layer of the atmosphere, and a lower resolution  
5 of 50 km.

### 3.3 Global chemistry transport model

In order to provide boundary conditions to the regional chemistry transport model and assess the role of global atmospheric chemistry changes on regional air quality we use the LMDz-OR-INCA chemistry-climate model (Folberth et al., 2006; Hauglustaine et al., 2004). The model is run with a horizontal resolution of 3.75° in longitude and 2.5° in latitude and uses 19 vertical levels extending from the surface to 3 hPa. Further  
10 details on the model setup can be found in (Szopa et al., 2012).

The three dimensional fields of 13 gases (including ozone, methane, carbon monoxide, PAN, HNO<sub>3</sub>, etc.) as well as various particulate matter compounds (dust, sulphate, black and organic carbon) are then used as boundary conditions for the regional AQ  
15 model. Given that we focus on background changes, monthly mean fields averaged over a 10 yr period are used. It should be noted that these background changes combine the impact of distant air pollutant emissions and global climate change since they are based on climate-chemistry simulations.

### 3.4 Regional chemistry transport model

The CHIMERE<sup>3</sup> model (Bessagnet et al., 2008; Menut et al., 2013) is used to compute regional air quality. The model is used by a number of institutions in Europe and beyond for event analysis (Vautard et al., 2005), policy scenarios studies for the French Ministry of Ecology, the European Commission and the European Environment Agency, operational forecasts (Honoré et al., 2008; Rouïl et al., 2009; Zyryanov et al., 2011),  
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<sup>3</sup>[www.lmd.polytechnique.fr/chimere](http://www.lmd.polytechnique.fr/chimere)

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model intercomparison exercises (Solazzo et al., 2012a,b; van Loon et al., 2007; Vautard et al., 2007), long term hindcasts (Colette et al., 2011) and projections (Colette et al., 2012a; Meleux et al., 2007; Szopa et al., 2006).

In the present study, the model is used with 8 vertical levels extending from about 997 hPa to 500 hPa and a horizontal resolution of 0.5 degrees. The relatively coarse horizontal resolution compared to recent model intercomparison initiatives is a necessary trade-off for long-term simulations required for air-quality and climate simulations.

## 4 Results

The results of the integrated air quality and climate simulations are discussed in this section. Four scenarios are investigated. The present-day conditions are covered with both hindcast and historical simulations and two possible futures are investigated for 2050: one of them (reference) assuming no implementation of any specific climate policy while the second (mitigation) aims at keeping global warming below 2 °C by the end of the century. Table 2 proposes a synthetic view of the modelling experiments. The basic experiments that combine all factors (climate, long range transport and emissions) are discussed in Sects. 4.1 and 4.2 while the sensitivity simulations are the focus of Sect. 4.3.

In each case, the simulation covers 10 yr in order to gain statistical significance and minimise the effect of climate interannual variability. This choice of a relatively short time period was made as a compromise between computer time resources and length required to obtain a detectable signal.

### 4.1 Regional climate projections

Even if the focus of the present paper is on impacts for air quality rather than regional climate itself, we describe in this section the main features of the regional climate fields since they will have a critical impact on the modelled air quality.

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### 4.1.1 General circulation

The 10 yr seasonal mean sea level pressure for winter and summer is provided in Fig. 1 for the present day conditions as depicted in the climate model (historical simulation) and the reanalysis (hindcast). In both seasons, important differences are found between the two representations of the climate of the early 21st century. In winter the historical simulations exhibit a much more zonal flow with a deeper Icelandic low pressure system yielding stronger average Westerlies. In summer the differences are not that large. Nevertheless the Azores high pressure system is deeper yet smaller in size, so that average mean sea level pressure over Western Europe is lower than in the reanalysis.

Whereas it is meaningless to compare the future climate projections to the past reanalysis, we can mention that these two main features (the strong zonal circulation in winter and the relatively low pressures over Europe in summer) are maintained in both future scenarios (not shown).

### 4.1.2 Temperature and precipitations

The higher end of the temperature distribution also differs strongly when changing the large scale forcing. As shown in Fig. 2, the historical climate model is much colder than the reanalysed hindcast. This statement is true for both annual mean temperature ( $-0.88\text{K}$  in winter and  $-1.46\text{K}$  in summer) and the 95th percentile of summer daily mean temperature (left panels of Fig. 2) with an average bias over Western Europe ( $5^\circ\text{W}$ ,  $15^\circ\text{E}$ ,  $40^\circ\text{N}$ ,  $55^\circ\text{N}$ : see area on Fig. 7) of  $-1.57\text{K}$ . This average bias is partly compensated by an opposite bias over sea surfaces. Over continental areas the temperature bias can reach values as high as  $5\text{K}$ . It is noteworthy to emphasize that the 95th percentile of temperature in the 2050 projections is respectively  $1.91\text{K}$  (for the RCP8.5) and  $0.51\text{K}$  (RCP2.6) warmer than the historical climate, showing that the absolute differences between current and future climate are actually smaller than temperature biases in the present climate.

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Differences in daily precipitations are also shown (right panels of Fig. 2). Precipitations are a key variable for air quality because they drive wet scavenging which is an important sink for airborne particulate matter. The second line of Fig. 2 shows that the historical climate simulation is too wet compared to the reanalysis throughout Europe. For precipitations, the difference between the current and projected climate is also clearly lower than the differences of the two realisations of current climate.

### 4.1.3 Summary

At this stage we exhibited important differences between the reanalysed and climate simulations that will be used to drive the air quality modelling performed in the remainder of the study. We anticipate some of these features to have a detrimental impact on the simulation of air pollutant events.

It is not the purpose of this study to assess where such differences come from. In a nutshell we can point towards (1) the global climate model, (2) the dynamical regional climate downscaling, or (3) the choice of the time period. The IPSL-CM5-MR model is known to exhibit a cold bias of sea surface temperature over the North Atlantic as a result of a strong underestimation of the Atlantic meridional overturning circulation (Hourdin et al., 2012). The dynamical downscaling has been demonstrated to contribute to an additional cooling (Colette et al., 2012c; Menut et al., 2012). These discrepancies could also be an artefact of the relatively short time period (10 yr) that could be influenced by an unfavourable climate mode (of the North Atlantic Oscillation for instance). The importance of using long times series has been repeatedly emphasized in climate studies and this factor should be taken into account in future air quality and climate assessments when the computing resources are sufficient (Langner et al., 2012a).

Before concluding this section devoted to the climate projection it is important to keep in mind that it is not because the climate model exhibits a bias compared to a reanalysed hindcast that its projections are not robust. An over-fitted climate would perform ideally for the past, yet being very poor for future projections. That is why, in

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the vast majority of climate literature, model variability is investigated rather than absolute differences. When it comes to climate impact modelling the perspective changes however; and the absolute differences do matter, hence raising new challenges. We will discuss in more details in the remainder of the paper how such differences bear upon our confidence in air quality projections.

## 4.2 Projected changes in air quality concentration

Figures 3 and 4 display the historical, hindcast and projections for ozone and total PM<sub>2.5</sub> (including secondary aerosols) concentration fields. Absolute values are given for the historical simulation while differences relative to the historical simulation are provided for the remaining configurations. Such differences are only plotted where found to be statistically significant with a student *t*-test at the 95 % confidence level (the difference being set to zero where un-significant). A qualitative discussion is given in the present subsection. This discussion remains descriptive since the results introduced here combine the impacts of emission projections, climate change and long range transport. The investigation will be further quantified in the Sect. 4.3 regarding the attribution analysis.

### 4.2.1 Ozone

Projected ozone changes are discussed on the basis of two different metrics in Fig. 3. The average summertime daily maxima (based on 8-h running means) of ozone (O<sub>3</sub><sup>max</sup>) is provided since it can be readily compared with the literature. However, in order to perform an exposure-based assessment we also focus on SOMO35, an indicator designed to capture detrimental impacts of ozone on human health and defined as the annual sum of daily maximum over 35 ppbv based on 8-h running means (expressed in µg m<sup>-3</sup> day).

The average situation for the historical (2005) simulation resembles the usual picture (e.g. Colette et al., 2011): a sharp latitudinal gradient with the exception of pollution

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hotspots over Europe. The difference between the historical and hindcast simulation provided on the second row confirms that the climate model is less favourable to ozone build-up than the actual meteorology over the recent past, as anticipated in Sect. 4.1.2.

A closer look into the frequency of stagnation episodes suggests a limited responsibility of unfavourable weather regimes in the climate model. Even if (Manders et al., 2012) pointed out this factor, in our case the historical simulation is actually more conducive to stagnant summertime episodes that the hindcast with a frequency of calm days (average wind speed below  $3.5 \text{ ms}^{-1}$ ) of 31 % and 23 %, respectively, and a mean duration of calm spells of 2.45 and 2.16 days (see the similar findings of Menut et al., 2012; Vautard et al., 2013).

The differences in summertime temperature and incoming short wave radiation can also lead to an underestimation of biogenic emissions of ozone precursors. In particular, we found that isoprene emissions were 68 % higher in the hindcast than in the historical simulation. By looking at the range of correction factors of the biogenic emission model (Curci, 2006; Guenther et al., 2006) for the corresponding range of temperature and incoming short wave radiation, we found that the sensitivity to the radiation was twice as large as the sensitivity to the temperature bias, suggesting that minimizing biases in cloud coverage in the climate model would help to reduce the ozone bias.

Last, we can mention that temperature, incoming radiation, or even specific humidity can also play a direct role onto atmospheric chemistry, although these factors are much more difficult to isolate (Menut, 2003).

Both projections for 2050 indicate a decrease of daily maximum ozone compared to the historical climate simulation, but the magnitude of this decrease is moderate for the reference scenario. The situation is however more complex under the reference scenario for the ozone human health exposure index, since SOMO35 actually increases over a significant part of Europe. The mitigation scenario achieves a much higher degree of emission reduction. As a result, SOMO35 decreases sharply, especially in the Mediterranean area where the levels were highest. On a more quantitative basis, in order to emphasize the projected changes in high-exposure areas, we apply a weighting

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function to the SOMO35 fields depending on the population density. We find that the population-weighted SOMO35 increases by 8.8 % (standard deviation  $\pm 5.2$ ) in the reference scenario whereas it decreases by 79.6 % ( $\pm 2.1$ ) in the mitigation case.

#### 4.2.2 Particulate matter

The average fields of fine particles ( $\text{PM}_{2.5}$ ) in Fig. 4 for the historical (2005) simulation display local maxima over the main air pollution hotspots besides the large influx at the southern boundary of the domain (desert dust). The large bias towards too high precipitations (Fig. 2) in the historical climate simulation leads to an overestimated scavenging and the average load of  $\text{PM}_{2.5}$  over Western Europe is only  $5.5 \mu\text{g m}^{-3}$  instead of  $9.1 \mu\text{g m}^{-3}$  when using the reanalysis. This bias cannot be attributed to a discrepancy of the frequencies of stagnation events that are very similar on an annual basis: 12.9 % and 12.3 % for the historical and hindcast simulations, respectively.

The decrease by 2050 is very large, with  $\text{PM}_{2.5}$  concentrations dropping down below  $2 \mu\text{g m}^{-3}$  over continental areas in both future scenarios. As far as secondary inorganic aerosols are concerned it is worth mentioning that the small increase of  $\text{NH}_3$  emissions in the GEA projections (Colette et al., 2012b) is not reflected in the projected formation of particulate  $\text{NH}_4^+$ . Whereas  $\text{NH}_3$  emissions increase by 22 % and 21 % for the reference and mitigation scenario, respectively, between 2005 and 2050, we find that  $\text{NH}_4^+$  decreases from  $0.68 \mu\text{g m}^{-3}$  in the historical 2005 simulation to  $0.12 \mu\text{g m}^{-3}$  and  $0.02 \mu\text{g m}^{-3}$  in the reference and mitigation projection, respectively. This feature emphasises the probable limiting role of  $\text{NO}_x$  emissions through the availability of  $\text{HNO}_3$  in rural areas (Hamaoui-Laguel et al., 2012) that do exhibit a strong decrease in the future. The reason why such behaviour is not reported in coarse global chemistry transport model projections deserves further investigation (Fiore et al., 2012; Shindell et al., 2012).

In terms of exposure, we find that population-weighted  $\text{PM}_{2.5}$  decreases by 59.7 % ( $\pm 2.1$ ) and 71.4 % ( $\pm 1.3$ ) in the reference and mitigation scenarios, respectively. It appears that air quality legislation (that is identical in both scenarios) somewhat

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dominates the relative change in exposure to  $PM_{2.5}$ , the impact of the climate policy (that differs in both scenarios) is not as large as observed for the exposure to ozone.

### 4.3 Disentangling the driving factors

The projected exposure to air pollution discussed in Sect. 4.2 takes into account the whole range of processes playing a role in the future evolution of air quality: global and regional climate, chemical background changes as well as air quality mitigation measures. This modelling system also offers the opportunity to isolate the contribution of each driving factor to the overall projected change in the basic simulations discussed in Sect. 4.2.

#### 4.3.1 Methodology

We quantify the respective role of each process from sensitivity experiments consisting in replicating the decadal simulations with all things kept equal except one of the driving factors. In order to optimise the number of numerical experiments, we decide to focus primarily on the respective contribution of projected chemically active AP emissions and climate. Excluding chemical boundary conditions from the sensitivity analysis allows decreasing substantively the number of sensitivity experiments.

The list of experiments is synthesised in Table 2 where we find the four basic simulations, and the six additional sensitivity simulations for each scenario (reference and mitigation). The overall impact of climate, boundary conditions and AP emissions is obtained from the basic simulations by withdrawing (H) from (R) or (M). In order to investigate the regional effects of climate change, the first step consists in using constant present-day AP emission and boundary conditions and then change the climate forcing (R1 – H and M1 – H). However, in order to explore the climate response under gradually changing AP emissions – yet avoiding performing transient simulation – the sensitivity to regional climate change is also tested with future AP emissions (R3 – R4 and M3 – M4). Symmetrically, the impact of emissions under constant climate

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and boundary conditions is explored for the present climate (R2 – H and M2 – H) and the future climate (R3 – R5 and M3 – M5). Last, the impact of boundary conditions is derived from the differences R6 – H and M6 – H. We decided to ignore the impact of gradually changing climate and emissions on the role of the boundary conditions, in order to avoid increasing the dimension of the sensitivity matrix to be explored.

The results are provided in Figs. 5 and 6 as boxplots whose colour match the key provided in the last column of Table 2. Each sensitivity simulation is decadal. Instead of giving the difference of the temporal averages (such as on the maps in the previous figures), we first aggregate spatially by taking the mean over Western Europe (5° W, 15° E, 40° N, 55° N) and then we compute the distribution of differences between the two sets of decadal simulations: that is 55 independent combinations of individual years. These distributions of 55 differences are presented here as box and whisker plots where the boxes provide the three inner quartiles and the whiskers provide the extremes of the distribution. A cross is given where the distribution of difference is statistically significantly different from zero (student *t* test with a 95 % confidence interval).

Multi-annual sensitivity experiments are common practice in climate studies, but annual simulations are often used in atmospheric chemistry studies to investigate the impact of emission changes or boundary conditions. However, the spread of the distributions obtained here demonstrate the need to use multi-annual sensitivity simulations in order to provide a quantitative perspective of the uncertainty whereas the qualitative conclusions would be unchanged.

The differences between the sensitivity experiments performed under present-day or future conditions (the two shades of orange and blue) also emphasize the need to explore the impact of regional climate change and AP emissions under gradually changing conditions. Whereas the relevance of transient approaches are often pointed out in base-case projections (Langner et al., 2012a), it is not common practice in sensitivity experiments addressing the disentangling of various contributions (Hedegaard et al., 2012; Manders et al., 2012).

## 4.3.2 Results

### Ozone

Ozone is presented here (Fig. 5), as in Sect. 4.2, as the average summertime daily maximum as well as SOMO35 and we find again that the overall projection (including all factors: white boxes) consists in a decrease by 2050 for both scenarios for  $O_3^{\max}$  and for the mitigation scenario for SOMO35 while a small increase is found under the reference scenario for SOMO35. In all cases the changes are statistically significant.

We find that the role of AP emissions change (boxes in blue shadings) dominates over the impact of regional climate change (boxes in orange shadings). For SOMO35, the relative change attributed to climate ranges from 3% ( $\pm 8$ ) to 5% ( $\pm 10$ ), while the response when changing emissions ranges from  $-23\%$  ( $\pm 10$ ) to  $-43\%$  ( $\pm 72$ ). 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 (Fiore et al., 2012; Hedegaard et al., 2012; Katragkou et al., 2011; Langner et al., 2012a,b; Lei et al., 2012; Manders et al., 2012). The fact that we use air pollutant emission projections based on explicit mitigation policies adds robustness to this finding.

Regional climate is found to constitute a significant penalty under present-day emissions (dark orange box) according to all metrics and scenarios. However, the response is not that large: below about  $1 \mu\text{g m}^{-3}$  for  $O_3^{\max}$ . This moderate impact is not surprising compared to the figures reported elsewhere where differences rarely exceed a few ppb (Andersson and Engardt, 2010; Katragkou et al., 2011; Langner et al., 2012a,b), only (Manders et al., 2012) found increases that could reach  $5\text{--}10 \mu\text{g m}^{-3}$ . A more innovative finding lies in the assessment of the climate penalty under future AP emission (light orange box). We find that the penalty will decrease in magnitude and even become a net benefit for  $O_3^{\max}$  under the mitigation scenario. The fact that projected climate change can contribute to decrease ozone levels was never reported before and highlights the need to account for the AQ policies when addressing the climate penalty. Whereas

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there are examples in the literature of assessments including combined climate and emission changes, sensitivity attribution studies are systematically performed under present-day conditions. We show here that the future context must be accounted for, even in the sensitivity analysis.

Ozone projections in Western Europe are actually more sensitive to background concentrations changes than to the penalty/benefit brought about by regional climate change. The tropospheric background ozone change constitutes a penalty under the reference scenario and a benefit under the mitigation case. These opposite trends stem from the joint evolution of global emissions and global climate and were also reported in the global chemistry climate projections for these scenarios (Szopa et al., 2012; Young et al., 2012). It is worth emphasising that in the global CTM, chemistry and climate are addressed jointly, it is therefore not possible to isolate to what extent these opposite trends are a result of AP emission changes in distant areas or a result of global climate on chemistry. In the mitigation scenario the decreasing background ozone burden contributes to increasing the benefit already obtained thanks to the reduction of AP emissions. But in the reference scenario, the compensation between a lower magnitude of AP emission changes, and a penalty brought about by the increasing ozone background yields the penalty seen for SOMO35 in the net response.

As mentioned in the introduction, regional climate change acts on ozone through several pathways: (1) it favours the emission of important precursors such as biogenic volatile organic compounds, (2) it has an impact on both chemical kinetics (through temperature and water vapour availability) as well as photochemical processes (through the incoming short wave radiation) and (3) it drives the frequency of weather patterns favourable for the build-up of pollutants and the turbulent mixing in the planetary boundary layer.

Katragkou et al. (2010) demonstrated, on the basis of sensitivity simulations, that biogenic emission, temperature and radiation have a comparable contribution to simulated changes. With regards to biogenic emissions, isoprene is a major factor (Meleux et al., 2007). Here we found isoprene emissions increases by 2050 of 15 % and 34 % for

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the mitigation and reference scenario, respectively. These numbers are moderate compared to existing estimates of end-of-the-century changes reaching 100 % (Andersson and Engardt, 2010; Katragkou et al., 2011; Meleux et al., 2007) but they are in line with the 20 to 25 % increase in 2050 compared to 2000 for the RCP4.5 in (Langner et al., 2012b). The sensitivity study of (Andersson and Engardt, 2010; Katragkou et al., 2011) reports an increased production of  $O_3$  of  $1\text{--}2\mu\text{g m}^{-3}$  for a 30 % increase of biogenic emissions. While we cannot give comparable estimates without performing a dedicated sensitivity study, we can infer from existing studies that biogenic emission constitute probably a significant fraction of the  $O_3^{\text{max}}$  change attributed to climate change.

A last important feature of Fig. 5 regards the role of the meteorological driver. We pointed out in Sect. 4.2 that switching from a reanalysis to a climate simulation had a strong impact on modelled air quality. The brown boxes in Fig. 5 give a more quantitative view of this sensitivity where we find that SOMO35 is 22 % ( $\pm 11$ ) higher when using reanalyses compared to a historical regional climate model. Such behaviour was not unexpected: similar findings were mentioned in the few studies that proceeded to a similar comparison (Katragkou et al., 2011; Manders et al., 2012). Nevertheless this bias raises serious concern on the uncertainty of such assessments.

## Particulate matter

The same framework is applied to disentangle the different driving factors in the projections of particulate matter (Fig. 6).

Again, the contribution of AP emissions is found to largely dominate over the regional climate signal, in agreement with (Hedegaard et al., 2012). This feature is even more pronounced than for ozone and the net decrease for  $PM_{2.5}$  attributed to AP emission reaches  $-56\%$  ( $\pm 6$ ) and  $-65\%$  ( $\pm 6$ ) for the reference and mitigation scenarios, respectively, out of a net change (all factors considered) of  $-60\%$  ( $\pm 5$ ) and  $-69\%$  ( $\pm 5$ ). The

contribution of long range transport for  $PM_{2.5}$  is small because of their shorter lifetime but not negligible for the mitigation scenarios.

With the present set of climate forcing, we find that regional climate change constitutes a slight benefit for  $PM_{2.5}$  concentrations. The increase in precipitations in the future (Fig. 2) certainly participates to this trend. But the magnitude of this benefit will decrease gradually in the future down to becoming non-significant for the mitigation scenario.

This climate benefit for  $PM_{2.5}$  is contradictory compared to the penalty reported in previous studies (Hedegaard et al., 2012; Manders et al., 2012; Nyiri et al., 2010). The lack of robustness regarding the impact of climate on  $PM_{2.5}$  was pointed out for the US by Jacob and Winner (2009); Tai et al. (2012). The spread of precipitation projections in regional climate models (Christensen and Christensen, 2007) constitutes a major challenge in narrowing the uncertainty of the impact of climate on particulate matter.

The uncertainty brought about when switching from a reanalysis to a regional climate model was already a concern for ozone, but this feature is more prominent for particulate matter:  $PM_{2.5}$  concentrations are 60% ( $\pm 10$ ) higher when using reanalyses as a meteorological driver. It thus competes in magnitude with all the other factors, which was not systematically the case for ozone. This increased sensitivity was also reported by Manders et al. (2012).

The attribution analysis for individual particulate components (not shown) is in line with the main findings for  $PM_{2.5}$ : a domination of AP emissions, moderate contribution of boundary conditions and benefit of climate change. The only feature that is worth mentioning is a stronger impact of climate for nitrate and ammonia: from -5% ( $\pm 12$ ) to -14% ( $\pm 19$ ) depending on the scenarios, as compared to sulphates: from -1% ( $\pm 5$ ) to -3% ( $\pm 5$ ). This sensitivity highlights that beyond precipitations and the related washout (that do not discriminate particulate components) other climate factors (temperature, relative humidity) play a role in the formation of secondary aerosol species. If a significant sensitivity to climate was expected for sulphate (through water vapour changes and subsequent availability of the OH radical) (Hedegaard et al., 2008), our

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results show that ammonium nitrate is also affected by climate change (through the temperature dependence of its formation process) (Bessagnet et al., 2004).

### 4.3.3 Mapping the indicator of the climate penalty/benefit

The isolated contribution of regional climate change to the net projected air pollution change is given for both scenarios as maps in Fig. 7. These maps are a composite of the differences obtained when comparing the decadal experiments under future and current climate, with future and current emissions, i.e. an average of the orange boxes in Figs. 5 and 6. The indicator is coloured in red (blue) to indicate the penalty (benefit) brought about by climate change when it leads to increasing (decreasing) air pollutant concentrations.

In this figure, we only discuss SOMO35 since its response is very similar to  $O_3^{\max}$ . A penalty dominates over continental Europe with the largest increases found over southern Europe, while more modest increases are found over Northern Europe, even leading to decreases over the British Isles, corroborating the findings of (Andersson and Engardt, 2010; Langner et al., 2012b). The largest changes are not systematically located over areas exhibiting high ozone levels such as the Mediterranean, emphasizing the role of biogenic precursors (Meleux et al., 2007).

For  $PM_{2.5}$ , regional climate change constitutes mostly a benefit by decreasing the concentrations. Over Morocco a penalty is found, which can be related to the decrease of precipitation in this area (Fig. 2). The penalty over the North Atlantic under the mitigation scenario is likely attributed to sea-salts since significant increases of surface wind speed are found in this area in winter and spring under the RCP2.6. Amongst all constituents contributing to the total  $PM_{2.5}$ , only ammonia appeared correlated with the slight penalty over Germany indicating an exacerbated sensitivity of the ammonia formation process to climate parameters in this area.

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## 5 Conclusion

We presented an analysis of combined projections of air quality and climate impact at the regional scale over Europe under the latest CMIP5 climate scenarios produced for the Fifth Assessment Report of IPCC. The regional modelling system includes global and regional climate as well as global and regional chemistry. The global fields are those delivered in the context of well established international exercises (CMIP5 for the climate and ACCMIP for the chemistry). Emissions of trace species follow the recent Representative Concentration Pathways for the global models while an update is used over Europe by using the scenarios developed for the Global Energy Assessment.

The use of recent emissions and consistent suite of models offers the opportunity to confront our findings with the literature and identify robust features in the overall projections of air quality and possible penalty and benefits brought about by climate change. The present setup also allows performing sensitivity simulations in order to disentangle the respective contribution of climate, air quality mitigation and background changes.

An important approximation in the design of the modelling chain is that we used an offline regional air quality model, hence neglecting feedbacks of chemistry onto climate at the regional scale. The whole issue of short lived climate forcings is thus excluded from the present assessment (Grell and Baklanov, 2011; Löndahl et al., 2010; UNEP, 2011).

The first prerequisite when using an air quality model to investigate the impact of climate consists in switching the meteorological driver from reanalyses or forecast to a climate model. This step has critical consequences on the impact model. The climate fields that we used in the present study suffer from a cold and wet bias, as a result of a flaw in the North Atlantic oceanic circulation. When using climate fields instead of reanalyses, daily mean summertime ozone decreases from 90.5 to 84.8  $\mu\text{g m}^{-3}$  and annual mean  $\text{PM}_{2.5}$  decrease from 9.1 to 5.5  $\mu\text{g m}^{-3}$ . Similar biases were reported before (Katrakou et al., 2011; Manders et al., 2012), but this feature is of course sensitive to

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the climate model selected and others had more satisfactory results (Hedegaard et al., 2008).

Using an ensemble of climate models (such as the forthcoming CORDEX ensemble of regional projections) would allow minimizing the biases attributed to the climate model. Whereas it is common practice in climate impact studies, it raises a significant computing challenge for air quality projections that are often as demanding as the climate modelling itself. Alternatively, emerging initiatives proposing statistical adjustments of the climate model could be contemplated (Colette et al., 2012c).

Our air quality and climate projections indicate that exposure to air pollution will decrease substantively by 2050 according to the mitigation pathway (that aims at keeping global warming below 2 °C by the end of the century) where exposure weighted SOMO35 and PM<sub>2.5</sub> will be reduced by 79.6 % and 71.4 %, respectively. For the reference scenario (ignoring any climate policy) the perspective is more balanced with a slight increase of SOMO35 (8.8 %) while PM<sub>2.5</sub> nevertheless decreases (by 59.7 %).

As far as the impact of climate alone on the net projected change is concerned, some of the features obtained with this new modelling suite appear robust when compared to the literature (Hedegaard et al., 2008, 2012; Katragkou et al., 2011; Langner et al., 2012a,b; Manders et al., 2012; Meleux et al., 2007; Szopa et al., 2006). The geographical patterns of projected impact of climate on ozone indicate an increase over southern continental Europe and a decrease over Northern Europe and the British Isles. The decrease in the north western part of the domain is a very robust feature. As pointed out in Langner et al. (2012b), the increase over the southern part of the domain is more sensitive as it shifts from the continental surfaces (Hedegaard et al., 2012; Manders et al., 2012; Meleux et al., 2007) to a maximum over the Mediterranean (Andersson and Engardt, 2010). Our results are somewhat half-way between the two options.

The geographical patterns of the impact of climate on particulate matter appear much less robust, as emphasized by Tai et al. (2012). With the set of climate forcing used here, we obtain a benefit for PM<sub>2.5</sub> whereas penalties were reported by Hedegaard et al. (2012); Manders et al. (2012). This lack of robustness must be related to the

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spread of precipitation projections in regional climate models (Christensen and Christensen, 2007).

A quantitative comparison of the driving factors has been conducted. The climate penalty is compensated by the projected changes in precursor emissions and to a lesser extent by long-range transport. Whereas the first studies on the sole impact of climate on ozone pointed toward a strong penalty brought about by climate change, more recent assessments including air pollutant emission projections already emphasized the larger role of the latter (Hedegaard et al., 2012; Langner et al., 2012a). As far as long range transport is concerned, a significant contribution was already envisaged by Langner et al. (2012a); Szopa et al. (2006).

We conclude that the overall climate penalty bearing upon ozone is confirmed, and its geographical patterns present some degree of robustness. At the same time, its importance should not be overstated. On a quantitative basis, we find that the air quality legislation being envisaged today should be able to counterbalance the climate penalty. On the contrary, the sensitivity to background changes (resulting from both long range transport and the impact of global climate change on the ozone burden) was overlooked in the literature, whereas its impact competes even more than the climate penalty with the beneficial air quality legislation.

For particulate matter, the small benefit brought about by climate change is largely dominated by the response attributed to changes in air pollutant emissions, while the contribution of boundary conditions is moderate. We note however that there is no consensus whether climate change constitutes a penalty or a benefit for particulate matter (Jacob and Winner, 2009). At the same time a considerable attention is devoted to the investigation of direct and indirect impact of aerosols on climate. Increasing the robustness of the anticipated impact of climate change on particulate matter should become a key research priority in the coming years.

At this stage, our evaluation of uncertainty remains limited since the results are confined to a comprehensive and up-to-date but *individual* suite of models and scenarios. Our study calls for a more coordinated approach using an ensemble of models for both

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climate and air quality. While such a coordinated exercise has been conducted before at global scale (e.g. ACCMIP), there is no equivalent at the regional scale.

Would such an experiment be implemented in the future, there are good chances that the modelling community could provide more quantitative inputs in terms of climate penalty/benefit for ozone over Europe. It remains difficult to give an estimate of the level of understanding of the contribution of distant sources because of the lack of significant coverage in the literature devoted to regional air quality projections. However, this contribution is expected to be significant for ozone, perhaps even more so than the impact of regional climate change. The issue of particulate matter is much less mature, if the contribution of long range transport is probably limited, the impact of climate is uncertain.

*Acknowledgements.* The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 282687 (ATOPICA). The French Ministry in charge of Ecology also supported this activity in particular through its Primequal Programme, together with ADEME (SALUT'AIR). The GIS climat-environnement-société supported the ACHIA project. This investigation also benefited from helpful discussions with partners of the Topic Centre on Air Quality and Climate Mitigation of the European Environment Agency (Robert Koelemeijer – PBL, Rob Maas – RIVM, John von Aardenne – EEA). Om Tripathi (now at Univ. Arizona) is acknowledged for his work with the IPSLcm5 downscaling tools and Gabriele Curci provided insightful suggestions with regards to the biogenic emissions.

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**Table 2.** Synthesis of the model setup for the basic simulations (H, E, R, M discussed in Sects. 4.1 and 4.2) as well as for the sensitivity experiments (Sect. 4.3). The key to the legend of Figs. 5 and 6 is also given in the last column.

	Climate	Boundary Conditions	AP Emissions	Key to Figure 5&6
Historical (H)	1995-2004	1996-2005	CLE 2005	
Hindcast (E)	1998-2007 (ERA-interim)	1996-2005	CLE 2005	E-H
Reference (R)	2045-2054 / RCP8.5	2045-2054 / RCP8.5	CLE1 2050	R-H
Mitigation (M)	2045-2054 / RCP2.6	2045-2054 / RCP2.6	CLE2 2050	M-H
R1	2045-2054 / RCP8.5	1996-2005	CLE 2005	R1-H
R2	1995-2004	1996-2005	CLE1 2050	R2-H
R3	2045-2054 / RCP8.5	1996-2005	CLE1 2050	R3-R4
R4	1995-2004	1996-2005	CLE1 2050	R3-R4
R5	2045-2054 / RCP8.5	1996-2005	CLE 2005	R3-R5
R6	1995-2004	2045-2054 / RCP8.5	CLE 2005	R6-H
M1	2045-2054 / RCP2.6	1996-2005	CLE 2005	M1-H
M2	1995-2004	1996-2005	CLE2 2050	M2-H
M3	2045-2054 / RCP2.6	1996-2005	CLE2 2050	M3-M4
M4	1995-2004	1996-2005	CLE2 2050	M3-M4
M5	2045-2054 / RCP2.6	1996-2005	CLE 2005	M3-M5
M6	1995-2004	2045-2054 / RCP2.6	CLE 2005	M6-H

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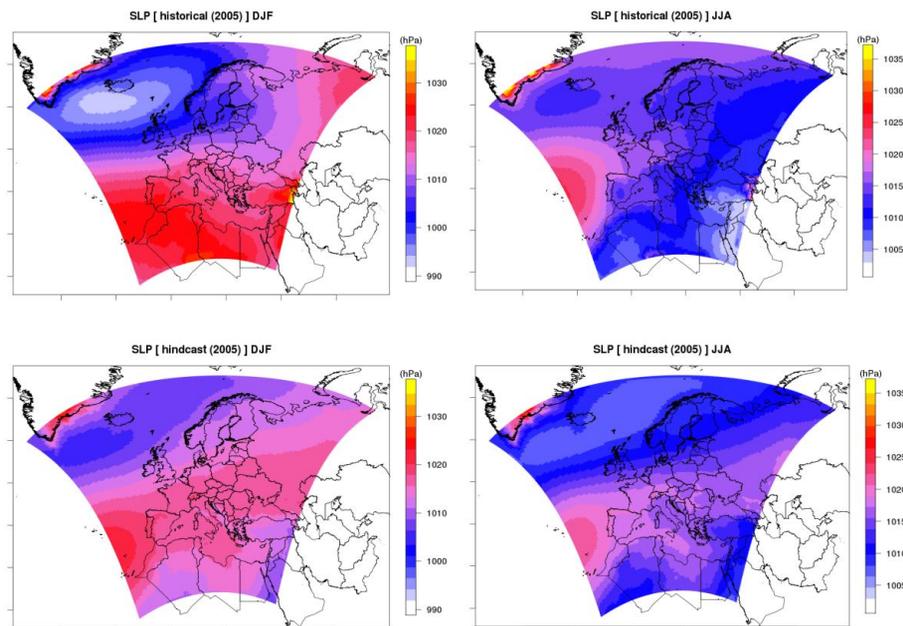
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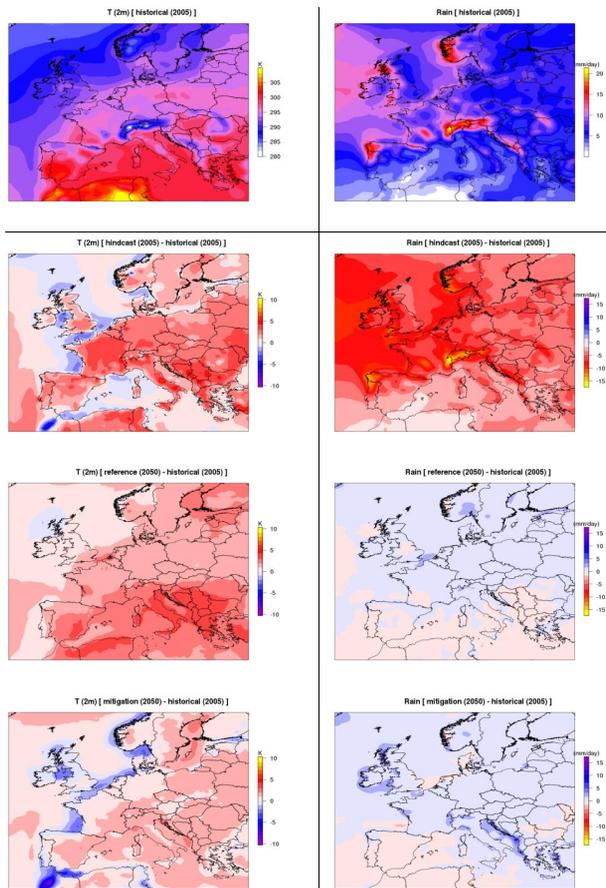
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**Fig. 1.** Mean sea level pressure in the regional climate model for winter (December-January-February, DJF, left) and summer (June-July-August, JJA, right) and for the two representations of current climate: historical (obtained with the climate simulation) and hindcast (obtained with the reanalysis). For each panel, the average is over 10 yr.

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**Fig. 2.** Left column: summer time (JJA) high 2-m daily mean temperatures (95th quantile, K) and right column: annual mean precipitations ( $\text{mm day}^{-1}$ ). On the first row we display the absolute results of the historical climate simulation and on the following row the differences compared to the later for the hindcast, the 2050 reference and the 2050 mitigation projections.

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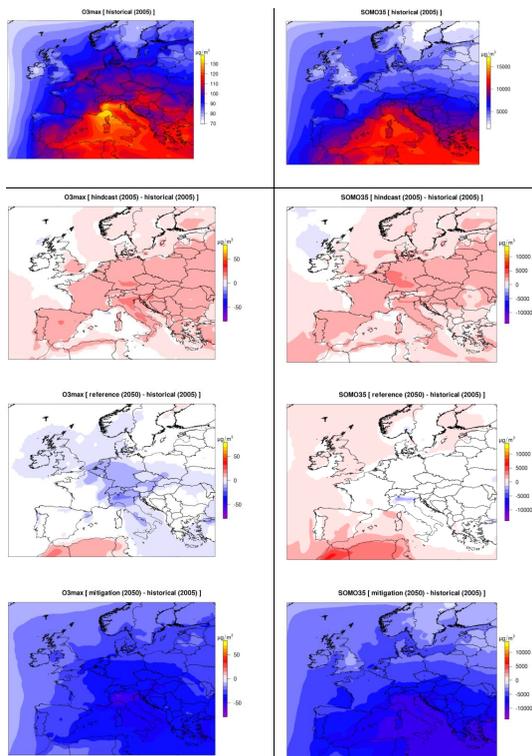
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**Fig. 3.** Top row (from left to right): average fields of  $O_3$  as summertime average of the daily maxima ( $O_3^{\max}$ ,  $\mu\text{g m}^{-3}$ ), and SOMO35 ( $\mu\text{g m}^{-3} \text{ day}^{-1}$ ) in the control (2005) simulation (averaged over 10 yr corresponding to the current climate). Following rows: difference between the simulations for the reanalysed hindcast and then for the reference and mitigation 2050 projections taken with respect to the historical climate simulation (2005). The differences are only displayed where significant given the interannual variability of ten years.

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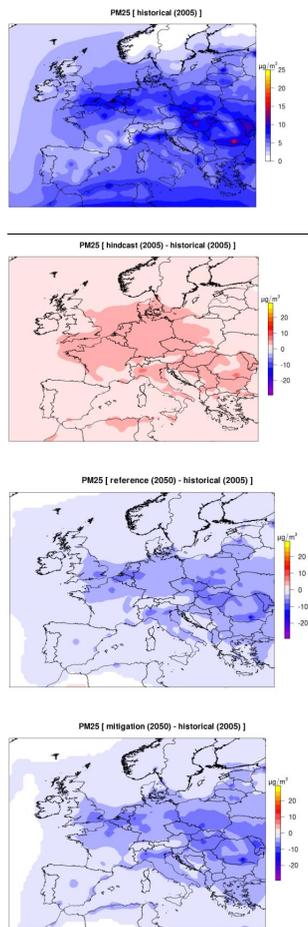
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**Fig. 4.** Same as Fig. 3 for  $\text{PM}_{2.5}$  (annual mean,  $\mu\text{g m}^{-3}$ ).

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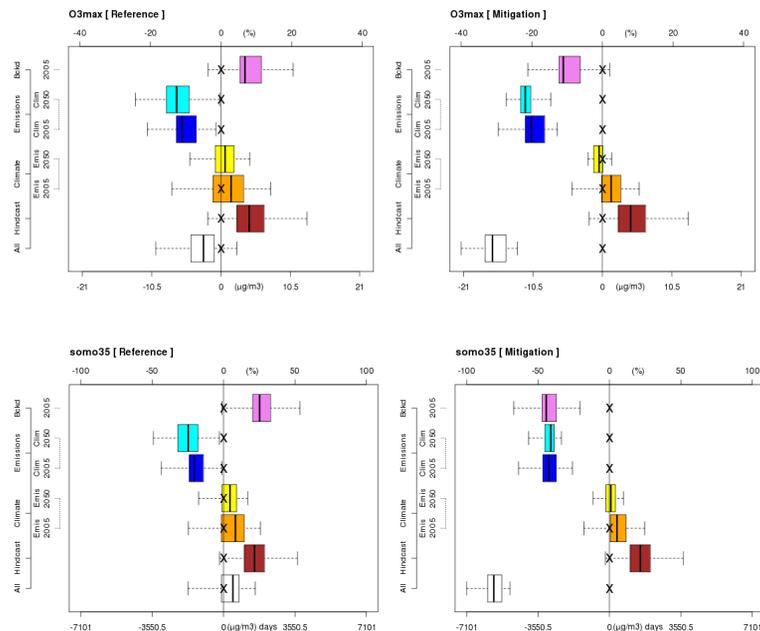
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**Fig. 5.** Contribution of the background air pollution (violet), regional emissions (blue shadings), and climate change (orange shadings) to the total projected changes (white) in  $O_3$  concentration as summer average of the daily max ( $O_3^{\max}$ ), and SOMO35 averaged over Western Europe in 2050 according to the reference (left) and mitigation (right) scenarios. In each case, we display net differences compared to a control selected to isolate one of the factor. A colour key to the scenario is given in Table 2. The sensitivity to the meteorological driver (either historical climate or reanalyses) is also given (brown). The sensitivity to emission and climate is investigated for both present and future conditions, hence the duplicate blue and orange boxes. A cross is marked when the distribution is significantly different from zero. The bottom axis provides the absolute difference and the relative difference with regards to the historical simulation is given as percentages on the top axis.

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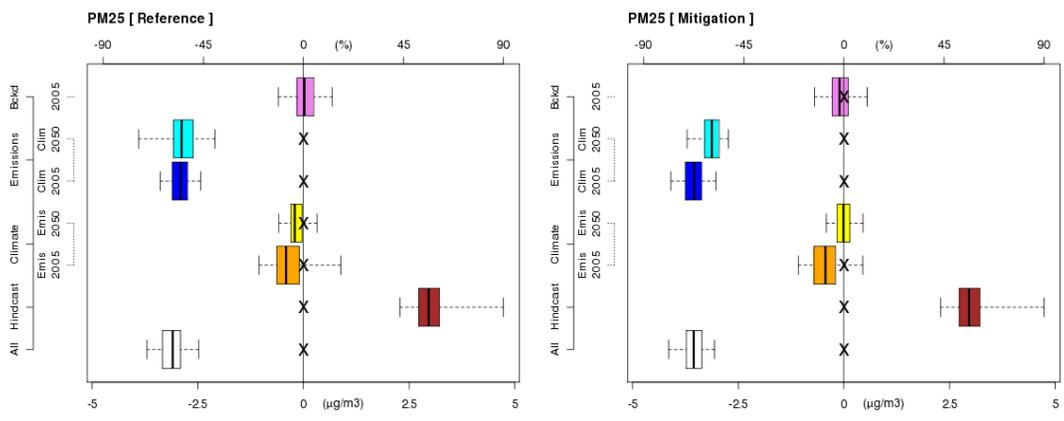
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**Fig. 6.** Same as Fig. 5 for  $\text{PM}_{2.5}$ .

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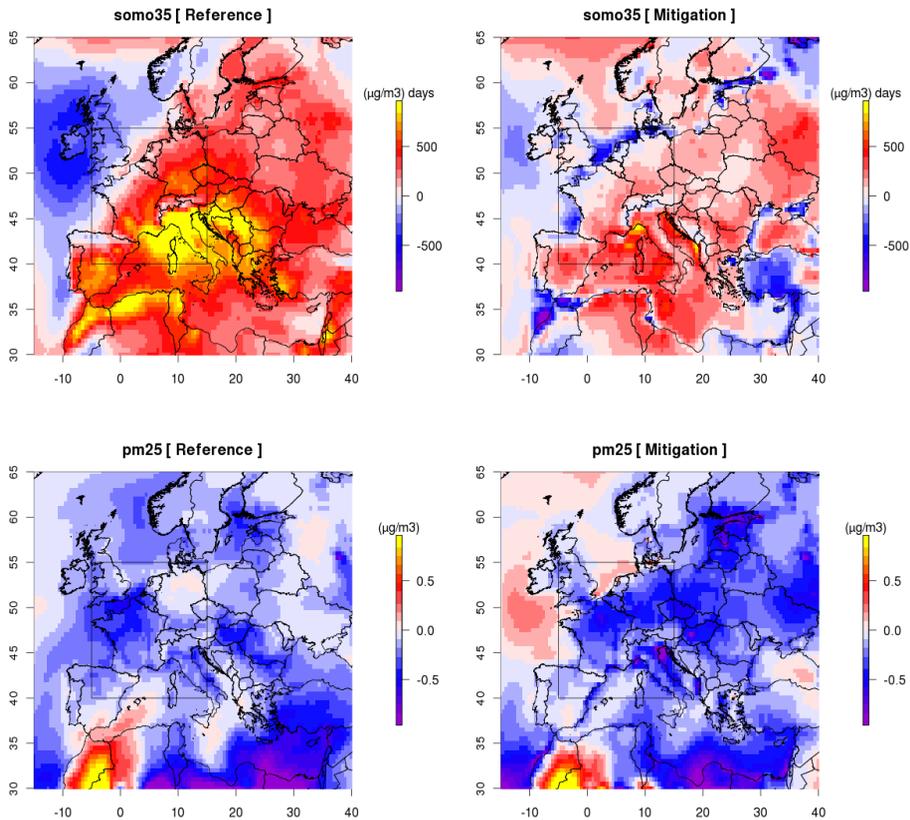
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**Fig. 7.** Map of the contribution of the regional climate to the projected change in air quality (from top to bottom: SOMO35, and  $PM_{2.5}$ ) for the reference (left) and mitigation (right) scenarios. A positive sign (red/yellow) indicates a climate penalty (increase air pollutant concentrations), whereas a negative sign (blue/violet) shows that future climate tends to reduce detrimental air pollution levels.