Anonymous Referee #1
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A methodology to "screen" regional climate projections in terms of their expected impact on future ozone and PM2.5 levels using a statistical model is presented. For PM2.5 the method only works for three out of eight regions in Europe which is a major concern, while for ozone it works better, six of eight regions.

Validation of the methodology was only done for one climate projection. Including one more of the regional climate projections in the validation of the methodology would make the paper more interesting and lend more confidence to the results presented.

It is our ambition to ultimately better understand the uncertainty that can be attributed to the climate forcing. To achieve this goal, we will force the CHIMERE CTM with alternative RCMs (in addition to the EuroCordex member of WRF-IPSL-INERIS that has been used here). However, because of the computational and storage demand required to retrieve such alternate forcing, we need to identify which RCM should be investigated in priority to offer an appropriate coverage of the range of uncertainty. It is the very purpose of the statistical ensemble exploration technique described in the present manuscript to define such priorities. However, at this stage alternative RCM forcings of the CHIMERE CTM are unfortunately not available to test the approach. Thus the only validation that we could include here was to test the statistical model on the basis of a future climate (2071-2100 in the RCP8.5), whereas it had been trained on a historical climate (1976-2005). The underlying hypothesis is that the historical range of meteorological parameters used to train the model will be exceeded in the future, therefore offering an appropriate testing dataset.

To better explain the difference between (i) ensemble of RCM forcing applied to CHIMERE and (ii) ensemble of RCM/CTM couples available in the literature, the following text has been added (page 3, line 15):

> "There are examples where more than two climate forcing are used, but then they are implemented with different CTMs, so that the uncertainties in the spread of RCM and CTMs is aggregated, thereby offering a poor understanding of the climate uncertainty. In addition, it should be noted that the choice of the climate driver is generally a matter of opportunity rather than an informed choice. These studies capture trends and variability but their coverage of uncertainty is not satisfactory in the climate change context."

To address the concern of the reviewer, the text has been modified page 28368 line 15 of the discussion paper (page 8, line 14 of the revised manuscript) in order to better explain why such a validation is not possible at present. The text now reads:

> "In order to evaluate the uncertainty related to climate change, the statistical models should be skillful for both pollutant concentrations over the historical period (training period) and in predictive mode. Alternative RCM forcing of the CHIMERE CTM could be used to test the approach. Unfortunately, such alternatives are not available at this stage. The statistical ensemble exploration technique presented here will ultimately allow selecting the RCM that should be used in priority to cover the range of uncertainties in air quality and climate projections. When such simulations become available, we will be able to further test the skill of the statistical model. However, so far, the only validation that could be included here was to rely on a future time period as validation dataset. The underlying hypothesis is that the historical range of meteorological parameters used to train the model will be exceeded in the future, therefore offering an appropriate testing dataset. The results of this validation are presented in section 3.2."

The regions for which no robust relationships were found should be mentioned in the abstract.

Given that the statistical model only works for three regions for PM2.5 the phrase "The climate benefit for PM2.5 was confirmed" seems too strong. Also in view of what is presented in the introduction about the divergence of previous estimates of the climate benefit for PM2.5 in Europe.

The sign of the climate change impact on particulate matter is indeed still unclear in the literature. Therefore the term "confirmed" was removed from the abstract. We have made clearer the performances of the statistical model per region in the revised version, also including the regions where the skills of the statistical model were not satisfactory. The abstract now reads:

"In the three regions where the statistical model of the impact of climate change on PM2.5 offers satisfactory performances, we find a climate benefit (a decrease of PM2.5 concentrations under future climate) of -1.08 (± 0.21) µg/m^3, -1.03 (± 0.32) µg/m^3, -0.83 (± 0.14) µg/m^3, for respectively Eastern Europe, Mid Europe and Northern Italy. In the British Isles, Scandinavia, France, the Iberian Peninsula and the Mediterranean, the statistical model is not considered skillful enough to draw any conclusion for PM2.5."

"In Eastern Europe, France, the Iberian Peninsula, Mid Europe and Northern Italy, the statistical model of the impact of climate change on ozone was considered satisfactory and it confirms the climate penalty bearing upon ozone of 10.51 (± 3.06) µg/m^3, 11.70 (± 3.63) µg/m^3, 11.53 (± 1.55) µg/m^3, 9.86 (± 4.41) µg/m^3, 4.82 (± 1.79) µg/m^3, respectively. In the British Isles, Scandinavia and the Mediterranean, the skill of the statistical model was not considered robust enough to draw any conclusion for ozone pollution."

The two paragraphs above were added page 28362, line 14 (page 2, line 4 of the revised manuscript) to precise and rephrase the climate impact on particulate matter, according to the reviewer comment. The results section and the conclusion have also been rephrased.

This divergence in existing estimates of the climate impact on particulate matter is one of our main motivations to better document uncertainties in the climate impact on air quality. One of the important limitations is that almost all studies rely on a single source of climate projection. The climate uncertainty is therefore very poorly addressed. In this study, the use of a statistical model allows discussing the robustness of the climate effect on PM2.5 on the basis of the whole EuroCordex ensemble. Even if the statistical model only works for three regions out of eight for the PM2.5, the climate ensemble includes multiple global climate models driven by different regional climate models. Therefore the climate uncertainty is better covered by this study than by a projection based on a single climate source. This point has been made clearer in the introduction (page 28364, line 4 in the discussion paper and page 3, line 31 in the revised manuscript) that now reads:

"This method allows selecting the members of the RCM ensemble that offer the widest range in terms of air quality response, somehow the "air quality sensitivity to climate change projections". These selected members should be used in priority in future air quality projections. A byproduct of our statistical air quality projections is that we explore an unprecedented range of climate uncertainty compared to the published literature that relies, at best, on two distinct climate forcings. The confidence we can have in these statistical projections is of course limited by the skill of the statistical model. Our approach of using a simplified air quality impact model but with a larger range of climate forcing can therefore be considered complementary with the more complex CTMs used with a limited number of climate forcings."

Although the focus of the paper is on the impact of climate change on air pollution it has been shown that projected European air pollution emission reductions has the potential to reduce both PM and ozone pollution in Europe to a large extent. This need to be mentioned in the introduction and the derived climate penalty/benefit should be contrasted to what could be achieved from emission reductions.

To address the reviewer comment, we have referred in more details to the literature in order to put in perspective the magnitude of climate and emission impacts. The following was added to the introduction (page 28363, line 6, of the discussion paper and page 2, line 27, of the revised manuscript):

"There is therefore a concern that in the future, climate change could jeopardize the expected efficiency of pollution mitigation measures, even if the available studies indicate that if projected emission reductions are achieved they should exceed the magnitude of the climate penalty (Colette et al., 2013;Hedegaard et al., 2013)"

A quantitative comparison of our estimates of the impact of climate change with the impact of emission reduction strategies reported in the literature was also added in the conclusion (page 28379, line 13, of the discussion paper and page 20, line 18, of the revised manuscript):

For PM2.5: "This impact of climate change on particulate pollution should be put in perspective with the magnitude of the change that is expected from the current air quality legislation. Such a comparison was performed by (Colette et al., 2013) who found (on average over Europe) a climate benefit by the middle of the century of the order of 0-1 µg/m3, therefore in line with our estimate but also much lower than the expected reduction of 7-8µg/m3 that they attributed to air quality policies."

For Ozone: "It should be noted that when comparing the impact of climate change and emission reduction strategies, (Colette et al., 2013) found a climate penalty of the order of 2-3µg/m3 (which is broadly consistent with our results given that they focused on the middle of the century) that could be compensated with the expected magnitude of the reduction of 5-10µg/m3 brought about by air quality policies."

Section 2.2: the performance of the CTM for the historical period must be discussed. To what extent is the model capable of capturing observed variability in PM2.5 and ozone in a statistical sense? More information is needed here or reference to previous work documenting the performance.

The CTM used here has been extensively used and validated in the past, several references were added to the text in Section 2.2 (page 7 line 28), also focusing on the specific use of the model in the climate change context:

"The Chemistry and Transport Model CHIMERE has been used in numerous studies: daily operational forecast (Rouïl et al., 2009), emission scenario evaluation (Cuvelier et al., 2007), evaluation in extreme events (Vautard et al., 2007), long term studies (Colette et al., 2011;Wilson et al., 2012;Colette et al., 2013) and inter-comparisons models and ensembles (Solazzo et al., 2012a;Solazzo et al., 2012b).

The model performances depend on the setup but general features include a good representation of ozone daily maxima and an overestimation of night-time concentrations, leading to a small positive bias in average ozone (van Loon et al., 2007). Concerning particulate matter, similarly to most state-of-the-art CTMs, the CHIMERE model presents a systematic negative bias (Bessagnet et al., 2014). Regarding more specifically its implementation in the context of a future climate, evaluations of the CHIMERE model are presented in (Colette et al., 2013;Colette et al., 2015) and also (Watson et al., 2015) and (Lacressonniere et al., 2016)."

Europe should be included in the title. There is a need for language editing. Some suggestions are listed below but there is more to do to improve the readability.

We modified the title to include Europe and the text to improve the overall readability; we appreciate the reviewer specific recommendations. All the technical and language comments have been taken into account.

Technical/language comments

- p28362 l8: dataset from a deterministic
- p28363 l12: cost of such technique
- p28363 l16: amounts
- p28364 l5: dataset from a deterministic
- p28364 l19: such a
- p28364 l25: projections
- p28366 l3: decrease of concentrations
- p28366 l28: square based on using
- p28367 l3: have been
- p28369 l13: to obtain a strong climate signal and significant results.
- p28373 l20: can also give an
- p28374l10: latter
- p28374 l12: displayed in
- p28374 l21: in Fig. 3
- p28374 l25: in Fig. 3
- p28375 l1: compared
- p28375 l2: episodes
- p28375 l17: similar to the
- p28376 l1: a deeper
- p28376 l9: of the selected
- p28376 l20: axis
- p28377 l12: rise differs between
- p28377 l13: largest difference
- p28377 l18: which shows the lowest increase
- p28377l22: is associated
- p28377 l24: In Fig. S5
- p28378 l8: meteorological drivers
- p28378 l9: projections
- p28378 l10; climate change
- p28378 l15: meteorological drivers.

Bessagnet, B., A. Colette, F. Meleux, L. Rouïl, A. Ung, O. Favez, C. Cuvelier, P. Thunis, S. Tsyro, R. Stern, A. Manders, R. Kranenburg, A. Aulinger, J. Bieser, M. Mircea, G. Briganti, A. Cappelletti, G. Calori, S. Finardi, C. Silibello, G. Ciarelli, S. Aksoyoglu, A. Prévôt, M.-T. Pay, J. M. Baldasano, M. García Vivanco, J. L. Garrido, I. Palomino, F. Martín, G. Pirovano, P. Roberts, L. Gonzalez, L. White, L. Menut, J.-C. Dupont, C. Carnevale, and Pederzoli, A.: The EURODELTA III exercise - Model evaluation with observations issued from the 2009 EMEP intensive period and standard measurements in Feb/Mar 2009, 2014.
Colette, A., Granier, C., Hodnebrog, Ø., Jakobs, H., Maurizi, A., Nyiri, A., Bessagnet, B., D'Angiola, A., D'Isidoro, M., Gauss, M., Meleux, F., Memmesheimer, M., Mieville, A., Rouïl, L., Russo, F., Solberg, S., Stordal, F., and Tampieri, F.: Air quality trends in Europe over the past decade: a first multi-model assessment, Atmos. Chem. Phys., 11, 11657-11678, 10.5194/acp-11-11657-2011, 2011.
Colette, A., Bessagnet, B., Vautard, R., Szopa, S., Rao, S., Schucht, S., Klimont, Z., Menut, L., Clain, G., Meleux, F., Curci, G., and Rouïl, L.: European atmosphere in 2050, a regional air quality and climate perspective under CMIP5 scenarios, Atmos. Chem. Phys., 13, 7451-7471, 10.5194/acp-13-7451-2013, 2013.
Colette, A., Andersson, C., Baklanov, A., Bessagnet, B., Brandt, J., H. Christensen, J., Doherty, R., Engardt, M., Geels, C., Giannakopoulos, C., B. Hedegaard, G., Katragkou, E., Langner, J., Lei, H., Manders, A., Melas, D., Meleux, F., Rouil, L., Sofiev, M., Soares, J., S. Stevenson, D., Tombrou-Tzella, M., V. Varotsos, K., and Young, P.: Is the ozone climate penalty robust in Europe?, Environmental Research Letters, 10, 084015, 10.1088/1748-9326/10/8/084015, 2015.
Cuvelier, C., Thunis, P., Vautard, R., Amann, M., Bessagnet, B., Bedogni, M., Berkowicz, R., Brandt, J., Brocheton, F., Builtjes, P., Carnavale, C., Coppalle, A., Denby, B., Douros, J., Graf, A., Hellmuth, O., Hodzic, A., Honoré, C., Jonson, J., Kerschbaumer, A., de Leeuw, F., Minguzzi, E., Moussiopoulos, N., Pertot, C., Peuch, V. H., Pirovano, G., Rouil, L., Sauter, F., Schaap, M., Stern, R., Tarrason, L., Vignati, E., Volta, M., White, L., Wind, P., and Zuber, A.: CityDelta: A model intercomparison study to explore the impact of emission reductions in European cities in 2010, Atmospheric Environment, 41, 189-207, 2007.
Hedegaard, G. B., Christensen, J. H., and Brandt, J.: The relative importance of impacts from climate change vs. emissions change on air pollution levels in the 21st century, Atmos. Chem. Phys., 13, 3569-3585, 2013.
Lacressonniere, G., Foret, G., Beekmann, M., Siour, G., Engardt, M., Gauss, M., Watson, L., Andersson, C., Colette, A., Josse, B., Marécal, V., Nyiri, A., and Vautard, R.: Impacts of regional climate change on air quality projections and associated uncertainties Climatic Change, Accepted, 2016.
Rouïl, L., Honore, C., Vautard, R., Beekmann, M., Bessagnet, B., Malherbe, L., Meleux, F., Dufour, A., Elichegaray, C., Flaud, J. M., Menut, L., Martin, D., Peuch, A., Peuch, V. H., and Poisson, N.: PREV'AIR An Operational Forecasting and Mapping System for Air Quality in Europe, Bulletin of the American Meteorological Society, 90, 73-83, 10.1175/2008bams2390.1, 2009.
Solazzo, E., Bianconi, R., Pirovano, G., Matthias, V., Vautard, R., Moran, M. D., Wyat Appel, K., Bessagnet, B., Brandt, J., Christensen, J. H., Chemel, C., Coll, I., Ferreira, J., Forkel, R., Francis, X. V., Grell, G., Grossi, P., Hansen, A. B., Miranda, A. I., Nopmongcol, U., Prank, M., Sartelet, K. N., Schaap, M., Silver, J. D., Sokhi, R. S., Vira, J., Werhahn, J., Wolke, R., Yarwood, G., Zhang, J., Rao, S. T., and Galmarini, S.: Operational model evaluation for particulate matter in Europe and North America in the context of AQMEII, Atmospheric Environment, 53, 75-92, 2012a.
Solazzo, E., Bianconi, R., Vautard, R., Appel, K. W., Moran, M. D., Hogrefe, C., Bessagnet,

B., Brandt, J. r., Christensen, J. H., Chemel, C., Coll, I., Denier van der Gon, H., Ferreira, J., Forkel, R., Francis, X. V., Grell, G., Grossi, P., Hansen, A. B., Jericevic, A., Kraljevic, L., Miranda, A. I., Nopmongcol, U., Pirovano, G., Prank, M., Riccio, A., Sartelet, K. N., Schaap, M., Silver, J. D., Sokhi, R. S., Vira, J., Werhahn, J., Wolke, R., Yarwood, G., Zhang, J., Rao, S. T., and Galmarini, S.: Model evaluation and ensemble modelling of surface-level ozone in Europe and North America in the context of AQMEII, Atmospheric Environment, 53, 60-74, 2012b.
van Loon, M., Vautard, R., Schaap, M., Bergström, R., Bessagnet, B., Brandt, J., Builtjes, P. J. H., Christensen, J. H., Cuvelier, C., Graff, A., Jonson, J. E., Krol, M., Langner, J., Roberts, P., Rouil, L., Stern, R., Tarrasón, L., Thunis, P., Vignati, E., White, L., and Wind, P.: Evaluation of long-term ozone simulations from seven regional air quality models and their ensemble, Atmospheric Environment, 41, 2083-2097, http://dx.doi.org/10.1016/j.atmosenv.2006.10.073, 2007.
Vautard, R., Maidi, M., Menut, L., Beekmann, M., and Colette, A.: Boundary layer photochemistry simulated with a two-stream convection scheme, Atmospheric Environment, 41, 8275-8287, 2007.
Watson, L., Lacressonnière, G., Gauss, M., Engardt, M., Andersson, C., Josse, B., Marécal, V., Nyiri, A., Sobolowski, S., Siour, G., and Vautard, R.: The impact of meteorological forcings on gas phase air pollutants over Europe, Atmospheric Environment, 119, 240-257, http://dx.doi.org/10.1016/j.atmosenv.2015.07.037, 2015.
Wilson, R. C., Fleming, Z. L., Monks, P. S., Clain, G., Henne, S., Konovalov, I. B., Szopa, S., and Menut, L.: Have primary emission reduction measures reduced ozone across Europe? An analysis of European rural background ozone trends 1996-2005, Atmos. Chem. Phys., 12, 437-454, 2012.