norden

Nordic Council of Ministers

Ved Stranden 18
DK-1061 Copenhagen K

www.norden.org

NORDISKE ARBEJDSPAPIRER

N O R D I C W O R K I N G P A P E R S

Impact of climate change on surface ozone and nitrogen deposition in Europe

An issue brief of results from the NMR-ENSCLIM project and
related studies

*J. Langner, D. Simpson, C. Andersson, A. Baklanov, M. Engardt, C. Geels,
J. Soares, and M. Sofiev*

<http://dx.doi.org/10.6027/NA2015-906>
NA2015:906
ISSN 2311-0562

This working paper has been published with financial support
from the Nordic Council of Ministers. However, the contents of
this working paper do not necessarily reflect the views, policies
or recommendations of the Nordic Council of Ministers.

NORDISKE ARBEJDSPAPIRER

NORDIC WORKING PAPERS

Impact of climate change on surface ozone and nitrogen deposition in Europe

An issue brief of results from the NMR-ENSCLIM project and related studies

J. Langner¹, D. Simpson^{2,3}, C. Andersson¹, A. Baklanov⁴, M. Engardt¹, C. Geels⁵, J. Soares⁶, and M. Sofiev⁶

¹Swedish Meteorological and Hydrological Institute, 601 76, Norrköping, Sweden

²EMEP MSC-W, Norwegian Meteorological Institute, 0313 Oslo, Norway

³Chalmers University of Technology, 412 96 Gothenburg, Sweden

⁴Danish Meteorological Institute, Lyngbyvej 100, 2100, København Ø, Denmark

⁵Department of Environmental Science, Aarhus University, 4000 Roskilde, Denmark

⁶Finnish Meteorological Institute, P.O. Box 503, 00101 Helsinki, Finland

Summary

Ambient air pollution is identified as one of the main threats bearing upon human health, with an estimated over 400 000 premature deaths in the EU every year (European Commission, 2013) attributed mainly to particulate matter and ozone. Continued excess nitrogen deposition due to emissions of air pollutants is also a major problem affecting sensitive ecosystems on land and in water. There is a concern that climate change could negate pollution mitigation strategies making them insufficient over the long run, e.g. through changes in temperature, precipitation and transport patterns (Jacob and Winner, 2009). This effect has been termed climate penalty in the literature and is generally assessed by driving chemistry-transport models by future climate projections assuming different scenarios for air pollution emissions. Here we present an analysis of the impact of climate change on future surface ozone concentrations and nitrogen deposition in Europe. The focus is on the period until ca. 2050. The results show that the climate penalty for surface ozone and nitrogen deposition is small in Europe for this time period compared to the expected benefits obtained from emission reductions.

1 Climate change and air pollution

The air pollution situation in northern Europe is significantly affected by long-range transport of air pollutants from continental Europe and further abroad. This in itself implies that long-term changes in weather patterns brought about by climate change has the potential to also change the air pollution situation in the region. Changes in climate can affect biogenic emissions of e.g. ozone precursors through changes in temperature and moisture conditions. Removal of air pollutants from the atmosphere is affected by a range of meteorological factors, including rainfall patterns, that is part of a change in climate. In addition the chemical processing of air pollutants and their precursors is affected by changes in for example temperature, sunlight and moisture content of the atmosphere. The relative

importance of these effects differs between air pollutants (Jacob and Winner 2009). The term “climate penalty” was first introduced by Wu et al. (2008) for the increase in surface ozone concentrations due to climate change, but it can also be used for the climate change effects on other air pollutants.

Change in climate is normally a gradual process with a time scale of decades. On shorter time scales it is not possible to detect statistically robust changes in climate due to the inherent, natural, variability of weather patterns from year to year. Projections of climate change have therefore mainly focused on time horizons towards the end of the 21st century, e.g. year 2070-2100. Initially climate change air pollution studies also focused on these longer time scales. However, significant reductions in air pollution emissions in Europe are projected on shorter time horizons. It is therefore also relevant to compare impacts of climate change towards 2050 with the impact of concurrent projected air pollution emission reductions although the uncertainty in the climate projection due to natural variability in the climate becomes relatively larger.

The above issues were pointed out in the Nordic Environmental Action Plan 2009-2012 with its objectives on “Climate and Air” and in the Klima- og Luftgruppens, KoL priorities for the period. The ENSCLIM project (Robustness of predictions of climate change impact on dispersion and effects of airborne pollutants in northern Europe) was funded with the aim to increase the knowledge base regarding climate impacts on air pollution with a focus on northern Europe. The project has involved five groups from four Nordic countries focusing on regional scale air pollution modelling. Each of these groups run their own model system on the European scale for policy support in their respective countries, including also the EMEP MSC-W model which is used for policy support in Europe and in the LRTAP convention. An explicit aim of the ENSCLIM project was to examine the spread of modelled changes in air pollution due to climate and emission changes. An important aspect of future air pollution in Europe is also the contribution from other continents – intercontinental long-range transport. By utilizing a model with a hemispheric domain from one of the participating groups this aspect was also covered in the ENSCLIM studies. Figure 1 depicts schematically the model chain used in ENSCLIM.

Figure 1. Model chain used in the ENSCLIM studies. Boxes shaded in blue represent the models executed in ENSCLIM while boxes shaded in yellow represent existing models and data bases that were utilized as input to the ENSCLIM models.

The ENSCLIM project has generated two main peer reviewed scientific publications. The first one on surface ozone and climate change, Langner et al. (2012b), and the second one on nitrogen deposition, Simpson et al. (2014a). The project has also contributed to several related publications from which additional results has been drawn for this policy brief (e.g. Engardt & Langner, 2013, Simpson et al., 2014b,c, Tuovinen et al. 2013). For further technical and methodological details the reader is referred to the respective scientific publications.

2 Surface ozone changes

There has been a significant increase in surface ozone since the beginning of the 20th century (Figure 2), which is largely attributed to changes in anthropogenic emissions of NO_x and other precursors (Parrish et al. 2009, Monks et al. 2009). The annual trends appear to have flattened out in Europe since about the year 2000. The reasons for this are not fully understood, but reductions in European emissions are certainly affecting ozone trends. In general mean ozone levels in Europe are increasing in wintertime because of the reduction in NO_x emissions (Wilson et al., 2012) and thereby reduced titration of ozone. Increasing hemispheric background ozone concentrations could also contribute. In summer, the European emission reductions act to help reduce ozone, although these are sometimes counteracted by increasing hemispheric background levels (e.g. Jenkin 2006, Simpson et al., 2014b).

Figure 2. Comparison of the 12-month running mean ozone concentrations from three northern European sites: Mace Head, Arkona, and Paris, and the marine Pacific boundary layer (MBL), Parrish et al. (2009).

The ENSCLIM ozone study focused on the climate impact, or penalty, for ozone in Europe around the middle of the 21st century. Figure 3 shows the ENSCLIM results for the change in daily maximum ozone concentration at the lowest model level between the time periods 2000-2009 and 2040-2049. As can be seen the change varies between models with the DEHM model showing the largest changes. Increases are mainly confined to southern Europe while there is no change or decrease simulated in northern Europe.

Figure 3. Simulated April-September change 2000-2009 to 2040-2049 in average daily maximum O_3 concentration at the lowest model level. Only changes that are statistically significant at the 95% level are plotted. Units ppb(v). Langner et al. (2012b).

In a related study using one of the ENSCLIM models Langner et al. (2012a) looked at the sensitivity of changes in surface ozone to different climate projections as well as to projected changes in European emissions and increasing hemispheric background ozone concentrations until 2050. Results for changes in daily maximum ozone concentrations are shown in Figure 4. Changes in emissions until 2050 clearly dominate the change in ozone in these simulations resulting in strong reductions in surface ozone over most of Europe. However, in western and northern Europe, increasing background concentrations could significantly offset the reduction due to emissions reductions in Europe.

Looking at the effect of climate alone, different climate projections do give a different magnitude of the changes in surface ozone towards year 2050 although the general pattern with increase in southern Europe and decrease in northern Europe remains. Significantly increasing ozone concentrations are, however, simulated over parts of the North and Baltic seas using one climate projection.

Figure 4. Change in summer (April-September), daily maximum, surface O₃ concentration from 1990-2009 to 2040-2059. (a) and (b) changes due to change in climate only; RCA3 downscaling of ECHAM5 and HadCM3, respectively. (c) ECHAM5 downscaling and change in European O₃ precursor emissions. (d) Increasing boundary case; the change due to combined change in climate, change in O₃ precursor emissions and an increasing hemispheric background of O₃ of 0.1 ppb(v)/yr. Non-significant changes at 95% confidence level are masked white, Langner et al. (2012a).

3 Nitrogen deposition changes

The dramatic increase in anthropogenic emissions after the 1940s, in both Europe and North America, resulted in substantial changes in reactive nitrogen, Nr, and sulfur, S, deposition. Reductions in emissions in Europe starting around the 1980s have resulted in significant reductions in oxidised Nr and especially S-compounds in the European atmosphere. Emissions of reduced Nr compounds have not declined to the same extent, and indeed in some areas NH₃ emissions are increasing.

Tørseth et al. (2012) have recently analysed trends in measurements of sulfur and Nr compounds, across Europe, based upon a selection of long-term sites from the EMEP network. The EMEP monitoring results for sulfate in air and precipitation over 1980-2009 reflect the emission changes throughout Europe, whereas the observed reductions in SO₂ are even greater than implied by emission reductions. Tørseth et al. (2012) compared the observed trends in sulfur, oxidised and reduced nitrogen compounds from 1980 (for S) or 1990 (for Nr) to 2009. The analysis of the Nr compounds was limited because of the lack of complete and consistent data across all years, but the results illustrate the significant changes in air quality that have taken place in this period. As shown in Figure 5 and discussed in more detail in Tørseth et al. (2012), the trends of S and Nr emissions are generally reflected in the measurements.

Figure 5. Average observed reduction in sulfur and nitrogen components compared to the emission reductions in Europe for the different ten years period from 1980 for sulfur and 1990 for nitrogen. Sulfur trends are calculated from the 14 sites with measurements of all three components since 1980, while for nitrogen the same number of sites are used, but it is not necessarily the same site used for all the components, Tørseth et al. (2012).

The second ENSCLIM study focused on changes in nitrogen deposition between 2000 and 2050 and in contrast to the first study on surface ozone the deposition study also included the effect of projected anthropogenic emissions changes in the same period both inside and outside Europe. Anthropogenic emissions for current legislation, CLE, for 2005 and 2050 were based on the data sets prepared by IIASA for the EU-ECLIPSE project.

Figure 6 shows the ensemble mean (over three ENSCLIM models) base case (2000s) and future (2050s) total deposition of oxidized nitrogen NO_y . When emission reductions are included (panel d) they dominate the outcome and decreased deposition is simulated across all of Europe apart from Turkey where emissions are projected to increase. Reductions in northern Europe are of the order $0.5\text{--}4 \text{ kg (N)ha}^{-1}$. Climate change alone (panel b) leads to increased total deposition of NO_y on the order of $0.1\text{--}0.5 \text{ kg (N)ha}^{-1}$ over most of southern and central Europe, while the effect in northern Europe is a slight reduction. Emission changes outside Europe (panel c) are simulated to result in a slight reduction in deposition.

Figure 6. Results from the ENSCLIM three-CTM ensemble, for (a) base-case deposition of NO_y (TDEP-NO_y, innermost legend), and changes in TDEP-NO_y (rightmost legend) resulting from (b) 2050s climate, (c) 2050s climate and boundary conditions and (d) 2050s emissions, climate and boundary conditions. Units: kg (N)ha⁻¹. Simpson et al., 2014a.

Figure 7. Same as Figure 6 but for reduced nitrogen, NH_x.

The result for total deposition of reduced nitrogen, NH_x , is quite different. In this case the simulated climate impact (Fig. 7b) is positive mainly in central Europe with $0.1\text{--}0.5 \text{ kg (N)ha}^{-1}$ and negative in most other regions of Europe by the same amount. The changes in emissions outside Europe (Fig. 7c) lead to a slight increase in deposition, while the European emission changes are simulated to lead to a more widespread increase in deposition (Fig. 7d). This increase in reduced nitrogen deposition is mainly the result of reduced sulfur and NO_x emissions and a resulting altered atmospheric lifetime of reduced nitrogen and to a lesser extent due to changes in NH_3 emissions which are almost unchanged for EU28 between 2005 and 2050 in the ECLIPSE emission scenario. Reduced emissions of sulfur and NO_x leads to decreased formation of ammonium sulfates and nitrates, which leaves a larger fraction of the emitted NH_3 remaining in the gas phase. Gaseous NH_3 readily dry deposits and has a shorter atmospheric lifetime than ammonium sulfate and nitrate. Decreased sulfur and NO_x emissions thus lead to shorter transport distances for reduced nitrogen and more local deposition of NH_3 .

5 Conclusions

Based on ENSCLIM and related studies the following conclusions can be drawn regarding future surface ozone concentrations in Europe:

- Projected reductions of anthropogenic ozone precursor emissions until 2050 will lead to strong (several ppb) reductions in surface ozone in Europe if realized, unless offset by increases in the hemispheric background ozone.
- Effects of climate change from 2000 until 2050 are generally small (ca. 1 ppb) and increases are mainly confined to southern Europe
- The four ENSCLIM models show a difference in sensitivity to climate change of about a factor of two, but geographical patterns of change are largely consistent for the same climate projection
- The main part of the difference in ENSCLIM model sensitivity is ascribed to underlying biogenic VOC (volatile organic carbon) emissions from vegetation, which vary by a factor of four in total emission of isoprene

Regarding future nitrogen deposition the following conclusions can be drawn:

- All ENSCLIM models clearly show that the impact of emissions changes until 2050 is much greater than the impact of climate change alone, or of both climate change and emissions changes outside of Europe.
- The model predictions for 2050 generally follow the emission changes, with significant reductions in oxidised N concentrations and depositions, but slightly increasing levels of reduced N-deposition.
- For reduced nitrogen, the 2050 emissions are predicted to cause a large increase in gaseous NH_3 deposition in most of Europe, but with large corresponding decreases in ammonium. This difference is caused by the much reduced levels of both SO_2 and HNO_3 in the future atmosphere, preventing the formation of ammonium sulfates or nitrates.

Acknowledgements

This policy brief was initiated and mainly supported by the Nordic Council of Ministers (EnsCLIM project, NMR no. KoL-10-04). Further support came through EU projects ECLAIRE (project no. 282910), MEGAPOLI (no. 212520), PEGASOS (no. 265148), TRANSPHORM (no. 243406), NMR FAN (kol-1204) and Danish ECOCLIM projects, and the Swedish Environmental Protection Agency through the research programme CLEO (Climate Change and Environmental Objectives) as well as EMEP under the LRTAP UNECE Convention.

References

- Engardt, M., and Langner, J.: Simulations of future sulphur and nitrogen deposition over Europe using meteorological data from three regional climate projections *Tellus B*, 65, 20348, <http://dx.doi.org/10.3402/tellusb.v65i0.20348>, 2013.
- European Commission, COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A Clean Air Programme for Europe /* COM/2013/0918 final */
- Jacob, D. J., and Winner, D. A.: Effect of climate change on air quality, *Atmospheric Environment*, 43, 51-63, 2009.
- Jenkin, M. E.: Trends in ozone concentration distributions in the UK since 1990: Local, regional and global influences. *Atmospheric Environment*, 42, 5434-5445, 2006.
- Langner, J., Bergstrom, R., and Foltescu, V.: Impact of climate change on surface ozone and deposition of sulphur and nitrogen in Europe, *Atmospheric Environment*, 39, 1129-1141, 2005.
- Langner, J., Engardt, M., and Andersson, C.: European summer surface ozone 1990–2100, *Atmos. Chem. Phys.*, 12, 10097-10105, doi:10.5194/acp-12-10097-2012, 2012a.
- Langner, J., Engardt, M., Baklanov, A., Christensen, J. H., Gauss, M., Geels, C., Hedegaard, G. B., Nuterman, R., Simpson, D., Soares, J., Sofiev, M., Wind, P., and Zakey, A.: A multi-model study of impacts of climate change on surface ozone in Europe, *Atmos. Chem. Phys.*, 12, 10423-10440, doi:10.5194/acp-12-10423-2012, 2012b.
- Monks P., Granier C., Fuzzi S., Stohl A., Williams M., Akimoto H., Amman M., Baklanov A., Baltensperger U., Bey I., Blake N., Blake R., Carslaw K., Cooper O., Dentener F., Fowler D., Fragkou E., Frost G., Generoso S., Ginoux P., Grewe V., Guenther A., Hansson H., Henne S., Hjorth J., Hofzumahaus A., Huntrieser H., Isaksen I., Jenkin M., Kaiser J., Kanakidou M., Klimont Z., Kulmala M., Laj P., Lawrence M., Lee J., Liousse C., Maione M., McFiggans G., Metzger A., Mieville A., Moussiopoulos N., Orlando J., O'Dowd C., Palmer P., Parrish D., Petzold A., Platt U., Poeschl U., Prévôt A., Reeves C., Reimann S., Rudich Y., Sellegri K., Steinbrecher R., Simpson D., ten Brink H., Theloke J., van der Werf G., Vautard R., Vestreng V., Vlachokostas C., von Glasow R.: Atmospheric Composition Change - Global and Regional Air Quality. *Atmospheric Environment*, 43, 5268-5350, 2009.
- Parrish, D. D., Law, K. S., Staehelin, J., Derwent, R., Cooper, O. R., Tanimoto, H., Volz-Thomas, A., Gilge, S., Scheel, H.-E., Steinbacher, M., and Chan, E.: Long-term changes in lower tropospheric baseline ozone concentrations at northern mid-latitudes, *Atmos. Chem. Phys.*, 12, 11485-11504, doi:10.5194/acp-12-11485-2012, 2012.
- Simpson, D., Andersson, C., Christensen, J.H., Engardt, M., Geels, C., Nyiri, A., Posch, M., Soares, J., Sofiev, M., Wind, P., and Langner, J.: Impacts of climate and emission changes on nitrogen deposition in Europe: a multi-model study, *Atmos. Chem. Phys.*, 14, 6995-7017, doi:10.5194/acp-14-6995-2014, 2014a.
- Simpson, D.; Arneth, A.; Mills, G.; Solberg, S. & Uddling, J. Ozone - the persistent menace; interactions with the N cycle and climate change *Current Op. Environ. Sust.*, 2014, 9-10, 9-19, 2014b
- Simpson, D.; Bartnicki, J.; Jalkanen, J.-P.; Hertel, H.; Hansson, H.; Langner, J. & Pryor, S. Atmospheric chemistry BACC II. Second BALTEX Assessment of Climate Change for the Baltic Sea Basin 2009-2014, Springer, Germany, 2014, In Press, 2014c

Tuovinen, J.-P.; Hakola, H.; Karlsson, P. E. & Simpson, D., Air Pollution Risks to Northern European Forests in a Changing Climate, Ch. 5 in *Climate Change, Air Pollution and Global Challenges Understanding and Perspectives from Forest Research*, D. Matyssek, R.; Clarke, N.; Cudlin, P. et al. (Eds.), Elsevier, Oxford, UK, 13, 77 – 99, 2013

Tørseth, K., Aas, W., Breivik, K., Fjæraa, A. M., Fiebig, M., Hjellbrekke, A. G., Lund Myhre, C., Solberg, S., and Yttri, K. E.: Introduction to the European Monitoring and Evaluation Programme (EMEP) and observed atmospheric composition change during 1972–2009, *Atmos. Chem. Phys.*, 12, 5447-5481, doi:10.5194/acp-12-5447-2012, 2012.

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, doi:10.5194/acp-12-437-2012, 2012.

Wu, S., Mickley, L. J., Leibensperger, E. M., Jacob, D. J., Rind, D., and Streets, D. G.: Effects of 2000–2050 global change on ozone air quality in the United States, *Journal of Geophysical Research: Atmospheres*, 113, D06302, 2008.