Interaction between climate change, air pollution and related impacts

Interaction between climate change, air pollution and related impacts

TemaNord 2008:602

© Nordic Council of Ministers, Copenhagen 2008

ISBN 978-92-893-1791-7

Print: Ekspresen Tryk & Kopicenter

Copies: 0

This publication can be ordered on www.norden.org/order. Other Nordic publications are available at www.norden.org/publications

Printed in Denmark

Nordic Council of Ministers

Store Strandstræde 18
DK-1255 Copenhagen K
Phone (+45) 3396 0200
Fax (+45) 3396 0202

Nordic Council

Store Strandstræde 18
DK-1255 Copenhagen K
Phone (+45) 3396 0400
Fax (+45) 3311 1870

www.norden.org

Authors:

K. M. Hansen¹, C. Geels¹, J. Brandt¹, B. Andersen¹, A. Baklanov², J. H. Christensen², O. B. Christensen², T. Ellermann¹, M. Engardt³, V. Foltescu³, A. W. Hansen⁴, E. Kaas⁴, P. E. Karlsson⁵, H. Pleijel⁶, A. Stohl⁷, L. Tarrasón⁸

With additional contributions from:

F. Boberg², J. Burkhardt⁷, D. Chen⁹, J. H. Christensen¹, H. Danielsson⁵, M. Drews², S. Eckhardt⁷, L. M. Frohn¹, A. Gross², G. B. Hedegaard^{1,2}, D. Hirdman⁷, M. Kahnert³, J. Klingberg⁶, U. Korsholm², A. Mahura², G. Pihl Karlsson⁵, K. Piikki^{10,6}, B. Hansen Sass², C. A. Skjøth¹, H. Sodemann⁷, M. Stendel², L. Tang⁹, K. Tørseth⁷, J. Uddling⁶

¹ National Environmental Research Institute, University of Aarhus, Frederiksborgvej 399, 4000 Roskilde

² Danish Meteorological Institute, DMI, Research Department, Lyngbyvej 100, Copenhagen, DK-2100, Denmark

³ Swedish Meteorological and Hydrological Institute, SE-601 76 Norrköping, Sweden

⁴ Niels Bohr Institute, University of Copenhagen, Juliane Maries vej 30, 2100 Copenhagen, Denmark

⁵ Swedish Environmental Research Institute (IVL), P. O. Box 5302, SE-400 14, Göteborg, Sweden

⁶ University of Gothenburg, Plant and Environmental Sciences, P.O. Box 461, SE-405 30 Göteborg, Sweden

⁷ Norwegian Institute for Air Research, Instituttveien 18, 2027 Kjeller, Norway

⁸ Norwegian Meteorological Institute, Niels Henrik Abels vei 40, 0313 Oslo, Norway

⁹ Earth Science Centre, University of Gothenburg, P.O. Box 460, SE-405 30, Göteborg, Sweden

¹⁰ University of Skövde, School of Life Sciences, P.O. Box 408, SE-541 28 Skövde, Sweden

Nordic co-operation

Nordic cooperation is one of the world's most extensive forms of regional collaboration, involving Denmark, Finland, Iceland, Norway, Sweden, and three autonomous areas: the Faroe Islands, Greenland, and Åland.

Nordic cooperation has firm traditions in politics, the economy, and culture. It plays an important role in European and international collaboration, and aims at creating a strong Nordic community in a strong Europe.

Nordic cooperation seeks to safeguard Nordic and regional interests and principles in the global community. Common Nordic values help the region solidify its position as one of the world's most innovative and competitive.

Content

Preface	7
Summary	9
Opsummering	11
1. Introduction	13
Climate change	15
Global and regional climate change projections	15
Impacts of climate change on air pollution	17
The effect of meteorological variability on measured and modelled air pollution levels	17
Projection of future air pollution levels in a changed climate	18
Possible impacts of climate change on O ₃	18
Possible impacts of climate change on N	19
Possible impacts of climate change on PM	19
The question of scale	19
Air pollution as a climate change driver	21
The role of aerosols	21
Online climate change and air pollution modelling	22
Conclusions	23
State of the science	23
The major uncertainties	23
The major challenges and future directions	24
The Nordic perspective	25
Overall recommendations	26
Appendix 1 Climate change – what we know and some myths	29
What has been simulated with the (global) climate models, and what is relevant for air pollution	29
What do we know (... or should know) about climate change in general.	32
Climate myths	33
Impacts of climate change on air pollution levels in the northern hemisphere with special focus on Europe and the Arctic	41
Summary	41
Introduction	42
Model systems	42
Results	44
Impacts and importance in relevant to policy development	46
Future outlook	47
References	47
Appendix 3 On the usage of an off-line chemistry transport model driven by a regional climate model to study air pollution and its impacts in the Nordic countries	49
Abstract	49
Introduction (Present status within the topic)	49
Results	50
Discussion	52
Conclusion	53
References	53
Appendix 4 Enviro-HIRLAM: on-line coupled modelling of meteorological and atmospheric chemical transport processes with two-way feedbacks	55

References:	59
Appendix 5 Climate forcing of aerosols with heterogeneous chemical composition and complex internal structure	61
Background.....	61
Activities at SMHI	62
References	65
Appendix 6 Future human and vegetation exposure for ozone - European emissions, hemispheric background, climate change and local geography.....	67
Abstract.....	67
Regional ozone levels	67
Local ozone concentrations near the ground.....	68
Trends in local ozone and meteorology in west Sweden.....	69
Discussion.....	69
References	70
Appendix 7 Global change and plant ozone uptake: Impact of elevated CO ₂ and meteorology	71
Abstract.....	71
Introduction	71
Results – dose-modifying factor related to plant ozone uptake.....	72
Discussion.....	74
Conclusion.....	75
References	75
Appendix 8 Transport of short-lived pollutants into the Arctic, and why it is important for climate.....	77
Abstract.....	77
References	77

Preface

This report contains the discussions and recommendations from a workshop held in Copenhagen 28-29 August 2008, where climate scientists and air pollution scientist from the Nordic countries were gathered to discuss the interaction between climate change, air pollution and related impacts.

The report contains a summary with four overall recommendations on how to proceed within the research field of interaction between climate change, air pollution and related impacts based on the discussions held during the workshop. Major findings and discussion points from the workshop are described in the main report. Scientific details can be found in the appendices and references herein.

Summary

The field of interaction between climate change and air pollution and related impacts is a relatively new research field. It is a complex field characterised by large uncertainties, and most work until now has focused on either climate change research or air pollution research without interaction between the two disciplines. At a workshop in Copenhagen 28–29 August, 2008 climate change scientist and air pollution scientists from the Nordic countries were gathered to discuss the interactions between climate change, air pollution and related impacts. On basis of the discussions, four overall recommendations on how to proceed on a scientific level within the research field of interaction between climate change and air pollution were made:

- There is a need for closer collaboration between air pollution and climate change scientists in order to identify the processes and parameters that need to be better described in climate models before more reliable projections of future air pollution levels from Chemistry-Transport Models (CTMs) can be obtained. As a first step a Nordic group of climate change and air pollution scientists should focus on cloud physics, as formation of clouds and precipitation are very important but not well described processes within both climate modelling and air pollution modelling.
- In Chemistry-Transport Models (CTMs) the various processes important for emission, atmospheric transport, chemical transformation as well as dry- and wet deposition needs to be analysed in detail (separately) in order to quantify the dependence (sensitivity) on climate change.
- With respect to air pollution levels it is important to quantify the signals from climate change and from changed emissions as well as the signal from the two combined on future air pollution levels. This should be done by increasing the sensitivity studies with both offline and online air pollution models.
- Finally, it is important to consider possible impacts on ecosystem and human health of climate changed induced changes in air pollution levels and exposure. This should be done by setting up an integrated impact assessment study, in which measurements, climate change modelling, air pollution modelling, and effect studies are combined to investigate a number of scenarios with changed climate, changed emissions and thereby related effects.

Opsummering

Vekselvirkningen mellem klimaændringer og luftforurening er et relativt nyt forskningsfelt, som er komplekst og præget af store usikkerheder. Det meste forskning har hidtil fokuseret på enten klimaændringer eller luftforurening, uden vekselvirkningen mellem de to discipliner. Klimaforskere og luftforureningsforskere fra de Nordiske lande var samlet ved en workshop i København 28.–29. august for at diskutere vekselvirkningen mellem klimaændringer, luftforurening og relaterede effekter. På baggrund af diskussionerne blev der udpeget fire overordnede anbefalinger angående hvordan man kan fortsætte indenfor forskningsfeltet om vekselvirkningen mellem klimaændringer og luftforurening.

- 1) Der er behov for et tættere samarbejde mellem luftforurenings-forskere og klimaforskere for at identificere de processer og parametriseringer der skal forbedres i klimamodeller før man kan opnå mere troværdige projektioner af fremtidens luftforurening fra kemi-transport-modeller. Som et første skridt bør en nordisk gruppe af klimaforskere og luftforureningsforskere fokusere på skyfysik, da dannelsen af skyer og nedbør er vigtige, men ikke vel beskrevne processer i klimamodeller og luftforureningsmodeller.
- 2) De processer der indgår i luftforureningsmodeller (vedrørende emissioner, atmosfærisk transport, kemiske reaktioner, våddeposition og tørdeposition) skal analyseres i detaljer (hver for sig) for at kvantificere de enkelte processers afhængighed (sensitivitet) af klimaændringer.
- 3) Med hensyn til luftforureningsniveauer er det vigtigt at kvantificere signalet fra klimaændringer og fra ændrede emissioner såvel som signalet fra kombinationen af de to. Derfor skal sensitivitets-studier med både offline og online luftforureningsmodeller intensificeres.
- 4) Det er vigtigt at tage mulige påvirkninger af økosystemer og menneskers helbred forårsaget af ændret luftforurening som følge af klimaændringer i betragtning. Dette skal gøres ved at igangsættes et “integrated impact assessment study”, hvor luftforureningsmålinger klimamodellering, luftforureningsmodellering samt effektstudier kombineres for at undersøge en række scenarier af klimaændringer, ændrede emissioner samt deres relaterede effekter.

1. Introduction

Air pollution has been studied intensively in the recent decades, which has led to regulation both in individual countries and in larger regions such as the EU. In recent years we have seen indications that the climate is changing due to the influence of anthropogenic emissions, with increasing mean temperatures and a growing number of extreme weather episodes. This has led to a growing interest in the effects of climate change on the future air pollution levels and the related impacts.

Climate model scenarios predict climate changes in the near future (50-100 years). It is generally expected that the global average temperature will increase in the future and the hydrological cycle will change, which will affect many if not all other meteorological parameters. Since the distribution of air pollution is highly dependent on the meteorology, it is reasonably to believe that the air pollution levels and distribution even with unchanged emissions will be changed in a warmer climate. Climate changes can also potentially alter the atmospheric transport pathways, so the transport of the air pollution, for example to the Nordic countries or to the Arctic will change. But air pollution components also have an effect on climate. As an example anthropogenically emitted aerosols can act as cloud condensation nuclei, which can alter the precipitation pattern and cloud albedo effect. Changes in the anthropogenic emissions of aerosols thus will affect the climate system.

Air pollution and their related effects on nature and human health has been studied intensively through several decades with measurement and monitoring campaigns, process studies, model studies and effect studies. The effect of increasing anthropogenic emissions of climate gasses on the future climate has been the subject of many model studies in the last couple of decades and several model intercomparison projects have been carried out in which both the performance and the results of the models are evaluated. However, the effect of climate change on air pollution levels and the interaction between air pollution and climate change is a subject that is relatively new and many processes and effects still needs to be quantified.

The report is based on the presentations from the workshop and the extended abstract written by the participants. These were centred around three major themes that forms the three chapters of the report: 1) Climate change, with presentations about global/regional climate change projections. 2) Climate change impact on air pollution, with presentation about the effect of meteorological variability on measured and modelled air pollution levels, on projected air pollution levels in a future climate on hemispheric and regional scale and on the impact of climate change on

ozone effect on vegetation. 3) The possible impact of air pollution as a climate change driver, with presentations about the effect of aerosols on climate and on-line climate change and air pollution modelling. The extended abstracts are found in the appendices.

There are several subjects that were not discussed at the workshop and they are not or only briefly described in this report. For example the impact of climate change on the Nitrogen loads to ecosystems, on the urban environment and on human health as well as the effects from acidification.

Climate change

Global and regional climate change projections

Projections of future climate change scenarios have been simulated with global scale climate models (GCM) for several decades. In recent years the focus has turned to ensemble studies to investigate the robustness of the predicted climate changes. These studies show that the global climate models and climate impact models generally agree on several issues (Appendix 1):

- The general climate evolution during the last 100 years or so can be simulated quite well.
- High latitudes warm (or cool) much more than low latitudes.
- The hydrological cycle intensifies as climate warms.
- Hydrologically driven weather systems (e.g. showers including thunder storms, tropical hurricanes, monsoons etc.) generally tends to intensify in a warmer climate.
- Mid- and high-latitude wet-deposition increases – particularly in the winter season – due to increased precipitation.

Of relevance to European climate change and European air pollution it is noted that temperature is projected to increase by some 2-4 degrees. In summer the largest increase is seen in southern Europe while the largest increase is seen in Northern Europe in winter. The summer warming is associated with very dry conditions in the southern part of Central Europe and in the Mediterranean area, but also winter anomalous dry conditions prevail in the Mediterranean area. Winter high latitude precipitation is enhanced quite strongly. Mean wind conditions – according to mean sea level pressure changes – tend to be more westerly in winter. Both the changes in mean temperature, precipitation, wind, humidity and cloud cover, will impact the European air pollution chemistry also without any concurrent changes in the emissions (Appendix 1).

Impacts of climate change on air pollution

The effect of meteorological variability on measured and modelled air pollution levels

There is a large year to year variability in meteorological conditions, which affect air pollution levels. For example, the year to year variability in meteorology generally dominates over the year to year variability in emissions for PM_{2.5}, but it is very dependent on geographical region in Europe. The emissions of PM_{2.5} in 2010 are predicted to be reduced with 25–35% compared to emissions from 2000, however, this may “drown” in the effect of the meteorological variability, which is of the same order of magnitude, and may therefore not be observed. The emissions of PM_{2.5} in 2020 are predicted to be reduced with 35–50% compared to emissions from 2000, which is larger than the variability in meteorology, and may be observed. For O₃ the emission reduction from 2000 to 2010 is 5–7% which is approximately the same as the variability in O₃ concentrations induced by variability in meteorological variables. This is also the case for 2020. The meteorological driver of the chemistry transport model (CTM) is also important. In an experiment, the change of meteorological driver resulted in variations in concentrations of PM_{2.5} of the same order of magnitude as variations from year to year variability of meteorological variables. With respect to deposition the meteorological variability is the most important.

Air pollution monitoring sites all over Europe are applied to evaluate modelled air pollution levels. However, local features may affect the measured concentrations which make them less representative for a larger area and this thus results in bias when comparing with modelled concentrations that are averages over larger areas. For example, there can be considerable differences in ozone levels near the ground within relatively small geographical distances, because ozone levels near the ground are depending on local climatology, in particular air turbulence during night-time, which in turn is strongly depending on local geographical settings such as local topography. It is therefore important to understand which geographical area that a certain monitoring site represents (Appendix 6).

Projection of future air pollution levels in a changed climate

A few Nordic studies have been made to project air pollution levels in a future climate. These are made with either hemispheric (Appendix 2) or regional (Appendix 3) chemistry transport models (CTMs) using output from a climate model as meteorological driver. These models studies are typically made with fixed, present day emissions and the information derived from the studies thus indicates what the impact of climate change on air pollution levels under a specific climate change scenario will be. These changes can be enforced or counteracted by changes in emission levels or other parameters that affect air pollution emissions and transport such as changes in vegetation type and land use.

The predicted changed concentration and deposition patterns indicate among other things that source receptor relations may change following altered deposition patterns and longer residence times of many species in the future atmosphere (Appendix 3).

Possible impacts of climate change on O₃

Tropospheric ozone is one of the most important gaseous pollutants for effects on vegetation on a regional to global scale. It is also important for health effects and as a greenhouse gas. Global change involves several potential changes that may strongly influence ozone exposure. There are rising trends for background ozone, also in the Nordic region. Ozone uptake by vegetation is strongly modified by air and soil humidity, CO₂ concentration and temperature. A warmer, humid climate in combination with a longer growing season and a higher ozone background would enhance ozone uptake by vegetation, while dryer conditions and elevated CO₂ concentrations tend to reduce ozone uptake. Since ozone effects on plant are closely related to ozone uptake, risk assessment for ground-level ozone is very sensitive to the local, specific pattern of environmental change (Appendix 7).

The projected air pollution levels in a future climate indicate what the effect of climate change on ozone concentrations under specific scenarios are. The hemispheric scale model shows that ozone concentrations increase in the future, and the increase gets stronger with increasing latitude (Appendix 2). The regional scale model simulations show that the seasonal-mean ozone concentrations are expected to increase considerably in central and southern Europe, in particular during summer, whereas the Northernmost Europe is projected to experience lower ozone concentrations under future climate, especially during spring and autumn (Appendix 3). It should be noted that the two models apply different assumptions

about the emissions which could be the reason for different predictions of the ozone levels in Northern Europe.

The increasing ozone concentrations will have a profound effect on a number of measures used to assess impacts on human health and vegetation (Appendix 3). In the Nordic climate an increasing future potential for ozone effects seems to be rather likely although uncertainties are large in this assessment (Appendix 7).

Possible impacts of climate change on N

Regional model studies indicate that the deposition of reactive nitrogen over the Nordic countries is expected to change only little, except over the Norwegian coast where it will increase substantially due to anticipated increases in precipitation (Appendix 3).

Possible impacts of climate change on PM

Regional model studies show that the concentration of Secondary Inorganic Aerosols (SIA) will increase dramatically in continental Europe during all seasons except winter. The increase is largest around the Mediterranean area during summer as a result of changing the meteorology (drier and warmer conditions in central and southern Europe). The increase in atmospheric SIA concentrations is related to a decrease in wet deposition of sulphur- and nitrogen containing species, which will be the consequence of climate change in large parts of central and southern Europe. Large areas around the Mediterranean, France, Belgium and the Netherlands will receive 50%, or less, of current nitrogen- and sulphur d

The question of scale

It is important to find out at what scale the interaction of climate change and air pollution modelling is important. Downscaling with high resolution models add credibility to the predicted climate changes.

Climate change is usually considered at very large geographical scales. However, climate change at the local scale may also be important for local near-ground ozone levels, because they depend on local climatology, in particular air turbulence during night-time. This is in turn strongly depending on local geographical settings such as local topography (Appendix 6). Since ozone effects on plant are closely related to ozone uptake, risk assessment for ground-level ozone is very sensitive to the local, specific pattern of environmental change (Appendix 7).

Air pollution as a climate change driver

The role of aerosols

Aerosols are considered one of the least understood factors influencing the radiative budget of the terrestrial atmosphere. IPCC points out the following sources of error while estimating the aerosol forcing:

- representation of size distribution
- treatment of aerosol chemistry
- hygroscopicity and water adsorption
- parameterisation of sea salt and wind-blown dust generation
- vertical mixing and removal processes influencing vertical distribution of aerosols
- radiative transfer computations

Aerosols in nature can also have complex morphologies. Some types of aerosols can have non-spherical or rough surfaces, such as mineral dust particles. Others, such as soot and fly ash aerosols, typically consist of clusters of particles. Anthropogenic aerosols in polluted air masses often consist of inhomogeneous internal mixtures of different chemical compounds. The morphology effects are generally not considered in today's climate models. However, accumulating evidence suggests that the mixing state and shape of aerosols are equally important for accurately quantifying climate forcing by particles (Appendix 5).

Mixing state and shape are equally important for accurately quantifying climate forcing by aerosols. Yet, not only mixing state, but also shape of non-spherical particles have been consistently neglected in climate modeling. It is still common to employ the homogeneous sphere approximation for estimating the direct radiative forcing for aerosols (Appendix 5).

In the Arctic, aerosols enhance temperatures during winter because heat is trapped underneath the clouds. Black carbon (BC) changes the snow albedo during spring, which also acts to increase the temperature. In summer, aerosols act to decrease temperatures through their indirect and direct effects (Appendix 8). The major sources of BC are Asian fires and European anthropogenic emissions. A warm episode at Svalbard in April and May 2006 led to enhanced transport from Europe to the Arctic, which is likely to happen in a changed climate (Appendix 8).

Online climate change and air pollution modelling

Air pollution modelling has traditionally been made with a one way coupling between the meteorological models and the air pollution models, also called offline modelling, which means that meteorological data is used as input to the air pollution models and with no feedback to the meteorological models. With a two-way coupling (online) air pollution can affect the meteorological conditions in the model.

Enviro-HIRLAM is an example of an online coupled model for both short- and long-term simulations of both meteorological and chemical weather. It includes feedbacks, in the form of direct aerosol effects and the first and second indirect effects, between air-pollutants and meteorological processes (Appendix 4). Current progress in the Enviro-HIRLAM system development and its online coupled modelling applications are considered. Several sensitivity tests of offline versus on-line coupling in Enviro-HIRLAM at DMI as well as verification versus experiments are considered and results are discussed.

Online integration modeling considering feedback mechanisms is promising for the future and could be beneficial for model improvements in both the climate-meteorology and the atmospheric environment/chemical weather forecasting communities (Appendix 4).

Conclusions

State of the science

We can summarise what the present state of the science is within the research field of interactions between climate change and air pollution.

Regarding projections of the future climate, we know that the CO₂ level is increasing, which has a number of effects on ecosystems. The global scale climate models are in general good. They predict that the global average temperature increases and that the hydrological cycle intensifies as climate warms. We know that climate change will have a significant impact on air pollution on both global and regional scale. Model studies assuming constant anthropogenic emissions have shown that climate change alone will increase ozone levels in the Northern Hemisphere. Increased ozone levels will have adverse effects on vegetation and human health. Increasing ozone levels and water vapour will speed up the chemical reactions in the atmosphere which will lead to an increase in secondary inorganic aerosols (SIA) close to emission sources.

It is likely that at high latitudes the increase in precipitation will decrease the concentrations of particles and increase the deposition of sulphur and nitrogen. In regions with decreasing precipitation the particle concentrations will increase. Source receptor relations may change following altered deposition patterns, and many species will have longer residence times in the future atmosphere.

The major uncertainties

There are at present some major uncertainties within the research field of interaction between climate change and air pollution.

With respect to the climate models, there are uncertainties due to observational limitations, in future emissions of both greenhouse gasses and aerosols, and the natural variability of the climate system is uncertain as well as in the response of the climate system to changes in emissions of greenhouse gasses and aerosols. Furthermore, the performance of regional scale climate models is uncertain, for example regarding the predicted precipitation and cloud cover. The uncertainties arise because the regional climate models are constrained by the chosen climate gas emission scenario and the dynamics of their driving global climate model. Studies have shown that different global models on the boundaries of the regional climate model results in different regional climate projections.

To accurately project the future air pollution concentrations on a regional level requires knowledge of future emissions and background concentrations of the chemical species of interest as well as their precursors. This requires coupling to global chemistry transport models (CTMs) driven by global climate models and realistic emission scenarios.

At present too little is known about the suitability of the physical and chemical process parameterisations in present day CTMs for describing these processes in a future climate. There are several process descriptions that we need to investigate further, such as:

- Wet deposition of air pollution
- Dry deposition processes
- Convective processes and vertical exchange
- Natural emission sources

There are also large areas of uncertainties in the impact of air pollution on climate change, for example:

- Impact of aerosols on radiation
- Impact of aerosols on cloud formation and precipitation
- Impact of aerosols on climate on a regional scale
- Impact of black carbon on snow albedo in the Arctic
- The role of O₃ as a climate gas in the Arctic

With regards to ozone, the measured levels in northern Europe are under the influence of two large-scale changes: reductions of European ozone precursor emissions and increasing hemispheric background concentrations. The net result of these changes for ozone levels and exceedances of air quality standards remains to be established. It is furthermore important to understand the cause behind the high spring ozone levels in air originating from northern latitudes; in what we would consider as relatively “clean air” (see Appendix 6).

The major challenges and future directions

With respect to climate models, we need to quantify the uncertainty on precipitation and cloud cover in regional scale climate models.

We also need to further study the variability of air pollution in a changed climate, e.g. by performing CTM simulations with climate data that spans the current uncertainty of regional climate simulations in Europe and to try to establish robust findings. It is also important to quantify the relative role of anticipated climate change in relation to changes in future European emissions and changing hemispheric background. Analysis of climate change effects on air pollution should be comple-

mented by process studies on the effect of changing meteorological parameters in air quality, in particular:

- The parameterisation of wet deposition of air pollutants
- Dry deposition processes – surface layer exchange, the relevance of surface wetness and soil moisture parameters
- Convective processes and vertical exchange in the atmosphere
- The role of natural emission sources

Further air pollution model studies are also needed to study the transport pathways in future climate and the link between climate change and exposure of air pollution of urban populations. We also need to make analysis of two-way feedbacks for climate and air pollution modelling

The relative impacts of a certain air concentration of ozone on the vegetation will be larger in northern Europe as compared with e.g. the Mediterranean region. Also, epidemiological studies indicate surprisingly large influence of ozone on human health in northern Europe. Hence, it is very important to establish dose-modifying factors both for the ozone impacts on vegetation but also most likely for the ozone impacts on human health in the Nordic countries.

Long time series of atmospheric pollutants are needed to see the effect of the climate change on measured levels. It is therefore important to continue the long monitoring series in order to quantify the impact of climate change on measured air pollution levels. It is important to continue the studies to investigate the representativeness of monitoring stations. It is also important to enhance the monitoring activity in the Northern part of the Nordic countries since this is where the major changes are projected to take place, whereas monitoring activities are mainly centred in the southern part where the majority of the population lives. In particular the high elevation mountain region in northern Fennoscandia is influenced by background ozone levels and it is unfortunate that there is at present no regular ozone monitoring station operating in this area at an altitude above 1000 m a.s.l.

The Nordic perspective

Based on the regional scale air pollution model studies the change in air quality in the Nordic countries due to changes in climate appears to be moderate compared to south and central Europe, where they will probably be substantial. However, the uncertainties in the calculations are large and the risk for deteriorating air quality in the areas of the Nordic countries with the present highest impact, i.e. the southern and western Scandinavia should not be underestimated.

The southern part of the Nordic countries are in the gradient zone of precipitation changes, which means that it is uncertain if the precipitation will increase or decrease. The effect on air pollution levels is therefore uncertain.

Arctic is an important area of interest for the Nordic countries and large climate changes are projected for the Arctic area. We need to study the impacts from climate change on air pollution levels in the Arctic area – e.g. POPs or heavy metals, but also PM and O₃. In the Arctic the effect of air pollutants on climate is also pronounced, e.g. with changed snow albedo in spring due to black carbon.

The humid climate promote leaf ozone uptake through the stomata, which means that the relative impacts of a certain air concentration of ozone on the vegetation will be larger in northern Europe as compared with e.g. the dry climate conditions in much of the Mediterranean region. Also, epidemiological studies indicate surprisingly large influence of ozone on human health in northern Europe. In the Northern part of the Nordic countries the spring ozone peak will in the future maybe coincide with the onset of the vegetation period, which potentially will increase the effect of ozone on vegetation.

Overall recommendations

This leads to four overall recommendations on how to proceed on a scientific level within the research field of interaction between climate change and air pollution were made:

1. There is a need for closer collaboration between air pollution and climate change scientists in order to identify the processes and parameters that need to be better described in climate models before more reliable projections of future air pollution levels from Chemistry-Transport Models (CTMs) can be obtained. As a first step a Nordic group of climate change and air pollution scientists should focus on cloud physics, as formation of clouds and precipitation are very important but not well described processes within both climate modelling and air pollution modelling.
2. In Chemistry-Transport Models (CTMs) the various processes important for emission, atmospheric transport, chemical transformation as well as dry- and wet deposition needs to be analysed in detail (separately) in order to quantify the dependence (sensitivity) on climate change.
3. With respect to air pollution levels it is important to quantify the signals from climate change and from changed emissions as well as the signal from the two combined on future air pollution levels. This

should be done by increasing the sensitivity studies with both offline and online air pollution models.

4. Finally, it is important to consider possible impacts on ecosystem and human health of climate changed induced changes in air pollution levels and exposure. This should be done by setting up an integrated impact assessment study, in which measurements, climate change modelling, air pollution modelling, and effect studies are combined to investigate a number of scenarios with changed climate, changed emissions and thereby related effects.

Appendix 1 Climate change – what we know and some myths

Eigil Kaas

*Niels Bohr Institute, University of Copenhagen, Juliane Maries vej
30, 2100 Copenhagen, Denmark*

What has been simulated with the (global) climate models, and what is relevant for air pollution

The recent AR-4 report from the IPCC working group 1 provides a comprehensive overview of our 2006 knowledge of climate change. Figure 1 shows multi model long term average results for the A1B scenario from a number of coupled atmosphere – ocean – sea ice – land surface models. Of relevance to European climate change and European air pollution it is noted that temperature increases by some 2-4 degrees. In summer the largest increase is seen in southern Europe while the opposite is the case in winter. The summer warming is associated with very dry conditions in the South Central Europe and in the Mediterranean area, but also in winter anomalous dry conditions prevail in the Mediterranean area according to model simulations. Winter high latitude precipitation is enhanced quite strongly. Mean wind conditions – according to mean sea level pressure changes – tend to be more westerly in winter. Both the changes in mean temperature, precipitation and wind will impact the European air pollution chemistry even without any concurrent changes in the emissions.

Figure 1. Multi-model mean changes in surface air temperature ($^{\circ}\text{C}$, left), precipitation (mm day^{-1} , middle) and sea level pressure (hPa , right) for boreal winter (DJF, top) and summer (JJA, bottom). Changes are given for the SRES A1B scenario, for the period 2080 to 2099 relative to 1980 to 1999. Stippling denotes areas where the magnitude of the multi-model ensemble mean exceeds the inter-model standard deviation. Source IPCC AR4.

Changes in the characteristics of precipitation (see Figure 2) should also impact aerosol pollution. The tendency for increased periods without precipitation may be most relevant in this context. This is a highly pronounced feature in Central and Southern Europe in summer. Climate model simulations of these features depend to some extent on model resolution, and the results may be more pronounced if high resolution regional climate models were used to obtain the same results as in Figure 2.

Figure 2. Changes in extremes based on multi-model simulations from nine global coupled climate models, adapted from Tebaldi et al. (2006). (a) Globally averaged changes in precipitation intensity (defined as the annual total precipitation divided by the number of wet days) for a low (SRES B1), middle (SRES A1B) and high (SRES A2) scenario. (b) Changes in spatial patterns of simulated precipitation intensity between two 20-year means (2080–2099 minus 1980–1999) for the A1B scenario. (c) Globally averaged changes in dry days (defined as the annual maximum number of consecutive dry days). (d) Changes in spatial patterns of simulated dry days between two 20-year means (2080–2099 minus 1980–1999) for the A1B scenario. Solid lines in (a) and (c) are the 10-year smoothed multi-model ensemble means; the envelope indicates the ensemble mean standard deviation. Stippling in (b) and (d) denotes areas where at least five of the nine models concur in determining that the change is statistically significant. Extreme indices are calculated only over land following Frich et al. (2002). Each model's time series was centred on its 1980 to 1999 average and normalised (rescaled) by its standard deviation computed (after de-trending) over the period 1960 to 2099. The models were then aggregated into an ensemble average, both at the global and at the grid-box level. Thus, changes are given in units of standard deviations.

The global climate models and climate impact models generally agree that:

- High latitudes warm (or cool) much more than low latitudes (polar amplification)
- The hydrological cycle intensifies as climate warms.

- Hydrologically driven weather systems (e.g. showers including thunder storms, tropical hurricanes, monsoons etc.) generally tends to intensify in a warmer climate.
- Mid- and high-latitude wet-deposition increases – particularly in the winter season – due to increased precipitation.
- The general climate evolution during the last 100 years or so can be simulated quite well.

A number of models entering Figure 1 and 2 include (relatively simple) interactive aerosol modules. This means that direct as well as indirect aerosol forcings related to cloud albedo and cloud life time are included. For the remaining models the impact of aerosols are prescribed.

What do we know (... or should know) about climate change in general.

The near surface temperature on Earth is determined by the total absorbed incoming solar radiation, and by the strength of the greenhouse effect. Pronounced long term global warming or cooling does not take place if there is no change in one or both these numbers.

Sometimes the following argument is heard: “Climate has varied a lot in the past. Why should anthropogenic climate change then be a problem?” This argument almost implies that climate can vary independently of fundamental physical laws determining the energy balance of our planet. This is of course not true. All major global climate changes and variations in the past have been associated with variations in the strength of the greenhouse and or the amount of solar heat absorbed in the climate system. If paleo-indicators of these fundamental numbers are at odds with other paleo-indicators of concurrent climate changes one should be very sceptical about the validity of both indicators. One explanation may e.g. be that a climate change indicator only reflects regional or hemispheric climate and not global climate.

There is reasonable agreement and consensus on the following important statements:

- Increasing atmospheric $[\text{CO}_2]$ heats the planet logarithmically and that $2 \times [\text{CO}_2] \sim 4 \text{ W/m}^2$.
- Climate sensitivity is uncertain, but model simulations and empirical investigations tend to agree on $0.75 \text{ K} / (\text{W/m}^2)$, i.e. $2 \times [\text{CO}_2] \sim 3 \text{ K}$ global warming.

Climate sensitivity including multi-centennial and millennial feedbacks from changing surface albedo is larger than $0.75 \text{ K} / (\text{W/m}^2)$. There is, however, not full consensus on this statement.

Climate myths

[CO₂] is probably lagging temperature by 200–1000 years during the last ice ages. Therefore CO₂ must be a consequence, not a driver, of temperature changes.

Several ice core drilling projects in Antarctica have documented a very close relationship between the CO₂ concentration in tiny air bubbles in the ice and the so-called deuterium excess δD , which is a measure of local temperature – see Figure 3. A careful analysis of the curves indicates that the CO₂ curve is lagging the temperature curve by some 200–1000 years, i.e. the [CO₂] variations follow the temperature variations. However, the magnitude of the lag is uncertain. When [CO₂] lags temperature it truly implies, that CO₂ is a consequence and not a driver of the temperature variations during the last 650.000 years. However, CO₂ is a highly important consequence since it acts as a feedback: cooler climate initiated by e.g. variations in the Earth orbit around the sun¹ implies decreased CO₂ concentrations in the atmosphere, hence decreased greenhouse effect. This decrease is caused by changes in the balances between carbon in the atmosphere and in the oceans. A relatively small part of the enhanced ocean uptake in cold periods can be ascribed to the simple fact that cold ocean water can hold more CO₂ than warmer water. Changes in the bio- and geochemistry are more important than the simple resolution effect. The low concentrations of CO₂ during ice ages provided a main cooling mechanism during the ice ages, which according to several studies was a main contributor to the existence of the cold ice age climate conditions. The time scale for CO₂ feedbacks is quite long – about 500–1000 years – because it takes time to reach new balances between CO₂ concentrations in the atmosphere and the oceans.

As seen from the natural climate system, anthropogenic release of CO₂ and of other greenhouse gases to the atmosphere constitute driver of climates, i.e. “pushes” on climate in the warmer direction. The additional carbon will interact with the natural carbon cycle responsible for the feedbacks just mentioned. The detailed behaviour of this interaction is one of the main contributors to uncertainty in future projections of climate change.

¹ Changes in the Earth orbit around the sun leads to changes in the amount of solar radiation received at different latitudes. According to the so-called Milanković theory these variations are the ultimate drivers of Ice ages.

Figure 3. Results from Antarctic Ice core analyses from two sites: Dome-C and Vostok. The red curve shows deuterium excess which is an indicator of local Antarctic temperature. Source: EPICA team.

[CO₂] increase (from 280 to 385 ppm) since pre-industrial times is not due to human emissions, but could simply be a consequence of the warming.

No known natural process could release so much CO₂ to the atmosphere so fast as it has occurred. For this simple reason it is unlikely that the statement could be true.

The natural isotopic composition of fossil fuels and biomass is different (with less heavy isotopes (¹³C and ¹⁴C)) from the natural composition in the oceans. Isotope investigations show that the oceans have absorbed about a third of the carbon related to combustion. Isotope investigations also eliminate the possibility that the atmospheric increase could come from the oceans because the atmospheric isotope composition is changing towards the composition in fossil fuels and not towards the composition in oceanic carbon.

Table 1. Estimated changes in carbon storages, emissions and fluxes relative to pre-industrial conditions. The unit is Gigaton carbon. Source: IPCC IR4.

	1980's	1990's	2000–2005
Atmospheric increase	3,3±0,1	3,2±0,1	4,1±0,1
Fossil fuels + cement prod.	5,4 ±0,3	6,4 ±0,4	7,2 ±0,3
Uptake in the oceans	-1,8 ±0,8	-2,2 ±0,4	-2,2 ±0,5
Net uptake on land	-0,3 ±0,9	-1,0 ±0,6	-0,9 ±0,6

*As a greenhouse gas water vapour is more important than CO₂.
Increasing [H₂O] could be the main reason for the ongoing warming.*

Water vapour contributes roughly² twice as much to the greenhouse effect as carbon dioxide. Water vapour acts, has acted and will act as a feedback for past, ongoing and future climate variations. According to climate model calculations this is the dominating feedback. The magnitude of coolings and warmings in the climate system would only be about half their actual magnitude had it not been for this feedback. Just as for the CO₂ concentration on ice-age time scales water vapour is a slave, not a driver, of climate change. The present human emissions of greenhouse gases acts as a driver of climate change on short time scales and the water vapour feedback is a fast feedback that will enhance the resulting warming significantly. However, water vapour will not be a driver in itself since human induced changes in the hydrological cycle are tiny as compared to the magnitude of the natural cycle.

Climate models are just models – why should we trust them?

Climate models are truly just models – but it seems as a “free lunch” to criticize them as unrealistic unless details about the criticism are provided. There will always be certain compromises in such models regarding the accuracy and consistency with which known physical and biogeo-chemical processes are approximated. To quantify how well the models treat one of the most fundamental processes, namely water vapour and the associated radiative fluxes in a varying climate one can compare model output with satellite data. Figure 4 and 5 – including figure texts – provide such a comparison. It is concluded that temporal variations in water vapour and related radiative fluxes are captured realistically in global climate models. Therefore it is reasonably safe to conclude that climate models are capable of simulating the most important feedback – the water vapour feedback – in a realistic manner.

² Due to spectral overlaps between water vapour and carbon dioxide it is not trivial to calculate the individual contributions to the greenhouse effect from multiple gases. If one assumes a percentage contribution from each of the gases in these overlapping bands, which corresponds to the relative magnitude of the full absorption (assuming absence of the other gas or gases) one will see that water vapour contributes about twice as much to the greenhouse effect under standard cloudy conditions as does carbon dioxide (Kiehl and Trenberth 1997).

Figure 4. Verification of water vapour simulated in a global climate model: The red curve shows percentage variations with time in the globally and vertically integrated water vapour in a simulation with the GFDL model. As lower boundary condition the model was provided with sea surface temperatures varying in time and space as observed. Otherwise the model was "free". The black curve shows a satellite micro-wave based observed estimate of the same quantity (SSM/I data). Despite the chaotic behaviour in the model atmosphere which is non-synchronous with the variations in the real atmosphere (since the model is dynamics are "free") the basic features are very similar. In other words the globally integrated atmospheric moisture content (and specific heat (not shown here)) are tightly coupled to the varying ocean state and this coupling is simulated very well by this (and other (not shown)) climate models. From Soden et al 2005.

Figure 5. The upper panel shows anomalies of global mean time series of brightness temperatures at a specific infrared satellite channel (T12). T12 is a measure of upper tropospheric relative humidity. The black curve shows satellite measurements and the red curve the corresponding GFDL-model response in the same simulation as shown in Figure 4. I.e. the red curve is what the satellite would have seen if the model data represented the underlying atmosphere. The green curve is obtained from a special model simulation where the model moisture variations artificially were held close to the observed values. The red-dashed curve shows corresponding results where the model relative humidity was fixed artificially. In summary the model reproduces the observed T12 and the trend

therein well. Furthermore, an assumption of constant relative humidity in the model gives T_{12} values that are similar to the standard model and to observed data.

The middle panel shows anomalies of global mean time series of brightness temperatures at a specific microwave satellite channel (T_2), which is a measure of tropospheric temperature. The two black curves (solid and dashed) is two different treatments of the original satellite data. The model captures the observed variations well, although there is some uncertainty in the observed estimates.

The lower panel shows $T_2 - T_{12}$ which is a measure of the upper tropospheric specific humidity. Specific humidity at these altitudes is highly important for the role of water as contributor to the Earth's greenhouse effect and to related water vapour feedbacks. The standard model simulation (red) and the version with artificially fixed relative humidity (dashed red) matches the observations quite well, while this is not the case for the model simulations with no trend in moisture. From Soden et al 2005.

Figure 6. Estimated radiative forcing from different sources since 1880. From Hansen et al. 2008.

Figure 7. Global average surface air temperature (SAT) in simulations with different coupled climate models. The black curve is the observed average SAT in both panels. The upper panel shows results from individual simulations (the spaghetti's) where different models were exposed to natural as well as anthropogenic forcings. The models generally capture the observed temperature evolution quite well. This is not the case in the lower panel where the models were only exposed to natural forcings (solar and volcanic).

The temperature trend in the free troposphere is less than that simulated with models. Therefore the models must be wrong.

It is correct that climate models simulate an enhanced warming in the middle and upper troposphere as compared to the simulated trend near the surface. The differential trend is most pronounced in the tropics. There are fundamental meteorological/physical reasons for this difference and the same difference in trend should be seen also for warming driven by other types of large scale forcing, e.g. solar forcing. Generally, the opposite differential trend should be seen during climate cooling periods.

It is highly questionable if there is any inconsistency between models and radiosonde observations regarding trends in the troposphere over the last 50 years. It is in fact wrong to state that the observed tropospheric trend is less than the corresponding trend simulated by climate models, or that it is less than the observed surface trend, which is fully consistent

with the models. The problem is that all types of observations representing tropospheric and stratospheric temperature suffer from severe homogeneity problems. Figure 8 demonstrates how different the various estimated trends are.

Inhomogeneity problems also exist for surface observations but here they are likely to be less severe since approximately the same instrumentation has been used for many decades. Furthermore, the surface observation network is denser and therefore it is more straightforward to use neighbouring observation stations to detect and correct for inhomogeneities.

Figure 8. Different measures of observed and modelled tropical tropospheric temperature trends. The data sets with the newest algorithms used to correct for observational inhomogeneities are Allen and Sherwood, RICH and RAOBCORE. The moist adiabat is a theoretical curve. Gray shading indicates the climate model spread.

The general trend in global temperature since 1998 is close to zero. [CO₂] has risen in the same period. Therefore it cannot be important.

It does not make much sense to use a 10 year period of observed surface air temperature (SAT) to conclude if a given type of climate forcing has been important or not during that period. This is because natural climate variations on regional spatial or short term (i.e. less than a few decades) global scale take place. Such changes are related to ocean heat transports, i.e. re-distribution of heat, and to temporal storage of heat in the oceans. Therefore one will need to analyse and eliminate the influence of such processes from the observed SAT record, before some relationship between external forcing of climate and SAT can be found.

Indirect solar forcings could be the reason for the on-going warming.

It has been suggested by Svensmark and Friis-Christensen that climate variations could be explained by varying flux of high energy galactic cosmic radiation (GCR). The idea is that variations in cosmic radiation can induce variations in ionization of the lower troposphere (below 3 – 5 km) and that this ionization in turn will stimulate the formation of small particles – so called cloud condensation nuclei. Thus, periods dominated by high GCR flux will also be dominated by enhanced ionization and thereby higher number concentration of cloud condensation nuclei, which again means whiter and more long lived low level clouds, i.e. clouds which tend to cool climate because they have a high albedo. The opposite is the case when GCR is low. Then low level clouds are less white and less widespread, and a relative warming of the climate should follow. The GCR cloud link is often referred to as an indirect solar forcing, since the GCR flux reaching the Earth is modulated by the solar activity. High/low solar activity means high/low shielding against GCR, hence smaller/larger GCR flux with subsequent reduced/enhanced cooling due to low level clouds.

Figure 9. Global mean temperature in the air just above the surface (blue curve), and percentage variations in GCR flux as estimated from low latitude neutron counts (red curve); note the inverse scale for the GCR which should correlate with the temperature curve according to the proposed idea.

While this is an interesting idea that may well have been relevant for some past climate variations it is highly questionable if it has contributed to the global warming during the last 30–50 years since there has been no general downward trend in the GCR as estimated from neutron counts. Figure 9 compares the observed global temperature near the Earth's surface with the GCR, and there is no sign of a trend in the GCR while this is definitely the case for the temperature. There is, however, some relationship between the observed temperature and the GCR in this period but this is on shorter decadal time scales. Appendix 2

Impacts of climate change on air pollution levels in the northern hemisphere with special focus on Europe and the Arctic

G. B. Hedegaard^{1,2}, J. Brandt¹, J. H. Christensen¹, J. H. Christensen², C. Geels¹, L. M. Frohn¹, K. M. Hansen¹, C. A. Skjøth¹, M. Stendel², and O. Bøssing²

¹National Environmental Research Institute, University of Aarhus, Frederiksborgvej 399, 4000 Roskilde, Denmark, ²Danish Climate Center, Danish Meteorological Institute, Lyngbyvej 100, 2100 Copenhagen, Denmark

Summary

A model system that is able to describe possible impacts of climate change on air pollution levels in the future has been established. The ab-

solute dominating impacts from climate change on a large number of the chemical species are related to the predicted temperature increase. As a consequence of this temperature increase, the temperature dependent biogenic emission of isoprene is predicted to increase significantly over land by the DEHM model. This leads to an increase in the ozone production and together with an increase in water vapour to an increase in the concentration of OH radicals. Furthermore this increase contributes to a significant change in the typical life time of many species, since OH are participating in a large number of chemical reactions.

Introduction

So far reduction of the anthropogenic emissions of chemical species to the atmosphere has been profoundly investigated. However, new research indicates that climate change also has a significant impact on the future air pollution levels. During the last couple of years, both global, hemispherical and regional modelling systems have been developed to describe the impacts of climate change on air pollution levels by different modelling groups all over the world. In the Department of Atmospheric Environment, National Environmental Research Institute (NERI) in Denmark, we have developed a hemispherical model system which shows good validation results. In the following section the model system will be described followed by some results and future out looks.

Model systems

The DEHM model system (see figure 1) consists of several combination of re-analysis data, meteorological input data to the DEHM model, which again can run in three different nested modes [Christensen, 1993, 1997 and Frohn et al., 2002]. The resolution of the mother domain is 150 km x 150 km and it covers the entire Northern Hemisphere. The largest nest is covering Europe with a resolution of 50 km x 50 km and the smallest nest is covering northern Europe with a resolution of 16.7 km x 16.7 km. The DEHM model consists of a whole family of models including a POP-version, a CO₂-version, a full chemistry-version and others.

In the DEHM modelling system an option for modelling the impacts of climate change has been included by using meteorological input of the future provided by a climate model. The setup is described in figure 2.

Figure 1 The DEHM Model system.

As the name of the climate model ECHAM4-OPYC3 indicates, this general circulation model consists of an atmosphere (ECHAM4) and an ocean (OPYC3) component [Roeckner et al., 1996, 1999]. The atmosphere model provides daily-averaged surface fluxes of momentum, heat and fresh water to the ocean model, which returns daily-averages of the sea surface temperatures, ice momentum and concentration as well as the ice and snow thickness. The output from the climate model is stored every six hours.

The six-hourly climate data is used as a one-way input to the DEHM model (full chemistry version of the DEHM model). The DEHM model also needs an emission input. The emissions of the primary pollutants consist of a combined set of data from the Global Emission Inventory Activity (GEIA) [Graedel et al., 1993], the Emission Database for Global Atmospheric Research (EDGAR) [Olivier et al., 1996] and finally from the European Monitoring and Evaluation Programme (EMEP) [Vestreng, 2001] for Europe.

The chemical transport model DEHM keeps track of the transport, chemistry, depositions and emissions of 63 chemical species and the model includes 120 of the most important chemical reactions between these species. Vertically the model is divided into 20 irregularly distributed layers extending from the surface of the earth to the 100 hPa pressure level. The ECHAM4 has a different resolution and therefore in order to use the meteorological fields as input data to the DEHM model a transformation of the meteorological data needs to be carried out before using it as input to the chemical transport model [Hedegaard, 2007]. So far there do not exist any projections of the anthropogenic emissions of the entire 21st century and therefore it is not possible to study the absolute effect of climate change and human activities in the 21st century. Until now, several experiments have been carried out at NERI solely to study

the effect from climate change on the air pollution levels in the future. The anthropogenic emission levels is kept at constant level, which enables the DEHM model to predict the changes in air pollution due to the impacts from climate change on the meteorology and biogenic emissions.

Figure 2 Off-line setup of the ECHAM4-OPYC3 and the DEHM model. The climate simulation is forced with IPCC A2 emission scenario. The output is saved every 6 hour and here after used as meteorological input to the chemical transport model DEHM. Besides the meteorological input, DEHM receives emission input from a combined data set (GAIA, EDGAR and EMEP).

Results

The prediction of the air pollution of the 21st century is carried out as a time-slices experiment in order to save computing time. The three selected time period are the 1990s, 2040s and the 2090s. The anthropogenic emissions are kept at a constant 1990 level in order to separate out the impacts from climate change. From a detailed analysis of many of the chemical species included in the DEHM model it is concluded that the trend is very similar for the first 50 year period (1990–2040) and the second 50 year period (2040–2090). Therefore only the changes between the 1990s and 2090s are discussed in the following.

The temperature is increasing everywhere in the domain and it is by the ECHAM4-OPYC3 model predicted to increase 3 °C on a global average. However, locally in the Arctic region a temperature increase of up to 11 °C is foreseen. This general temperature increase with local hot spots over Southern Europe and the Arctic is similar to other model results [Stendel et al. 2002].

The difference in the ten-year average ozone concentration of the two decades is displayed in Figure 3 (left plot). A latitudinal dependence is evident in this figure. Ozone concentrations increase in the future and the increase gets stronger with increasing latitude. North of approximately 30° N the increase is highly significant (cf. right plot of fig. 3). South of 30° N the difference in ozone concentration changes and in the equatorial areas the ozone concentration levels tend to decrease significantly between the two decades. However, also a blurred land-ocean contrast in the ozone increase is evident and the ozone concentration generally increases less over the ocean.

Figure 3 The difference in ozone concentration between the mean values of the two decades 2090s –1990s in percent. Right: The statistical significance of the changes of mean values between the two decades according to the t-test. The threshold value for significance is chosen to be within the 0.95 fractile corresponding to the 10% significance level (which is the same as the 1,734 percentile value in the plot). Red colours indicate a significant increase and green colours indicate a significant decrease.

The ozone production in the troposphere is strongly dependent on the presence of the precursors NO_x and Volatile Organic Compounds (VOC). In the experiment analysed here, the anthropogenic emissions are kept constant. However, VOCs also have biogenic emitters, which can alter their emissions due to changes in the meteorological conditions. The only natural VOC emission included in the DEHM model is the emission of isoprene. Isoprene is through participation in chemical reactions with OH, acting as a sink for OH radicals³. In DEHM, the submodel BEIS (Biogenic Emissions Inventory System) is included to account for the biogenic isoprene emissions (Guenther et al. 1995). Isoprene is emitted from trees and other plants and therefore primarily existent over land.

The concentrations of isoprene are predicted to increase significantly where there are emitters present (not shown), for further details see Hedegaard, 2007 and Hedegaard et al., 2008. The general increase in isoprene concentration over land due to the temperature increase can con-

³ Isoprene is also, through the role as ozone precursor, a source to the production of OH radicals.

tribute to explain the increase in ozone, which poses a blurred land-sea contrast in the distribution field. The projected observed level of isoprene will alter the ozone production in a positive direction and thereby enhance the ozone level. These findings are in line with other studies [Tuovinen et al., 2002, Langner et al., 2004, Murazaki and Hess, 2006].

Furthermore an enhanced conversion rate is found in this changed climate. By the projected general increase in ozone and in specific humidity (not shown), it can be concluded that DEHM predicts an increase in the reaction rates in a large number of chemical reactions over sea and at higher altitudes due to the resulting increase in hydroxyl radicals which will have a large influence on the life times of many chemical species. In Hedegaard (2007) it is shown that the life times of for example nitrogen dioxide will be reduced and lead to an increased level of nitrate and nitric acid. Also the sulphate production through the conversion of sulphur dioxide will increase in the future, for further details see Hedegaard, 2007 and Hedegaard et al., 2008.

Impacts and importance in relevant to policy development

The coupling of the ECHAM4-OPYC3 climate model and the chemical DEHM model is a very strong modelling tool with respect to studying impacts of climate change on air pollution. The model system has so far been established and shows fine evaluation results. A model system like this is very useful for both researchers and policymakers when assessment of the signal from climate change versus the signal from anthropogenic emissions needs to be carried out. The DEHM model includes many chemical species which is relevant both to human health and nature. For example tropospheric ozone, nitrogen dioxide and particles impacts strongly on human health by affecting the respiratory system, which can lead to increased mortality. Persistent Organic Pollutants (POP) can affect the well-being of both human and animals by destroying both the fertility and the ability to produce healthy progeny. Diseases like cancer and immune system failure can also be a result of increased POP pollution. Heavy metals on the other hand can effect the nervous and brain system of human and animals. Both heavy metals and POPs have a tendency to accumulate with in the food chain and therefore the strongest effects are found at the highest trophic level like for example human-beings.

Concerning the natural environment the DEHM model can be used with respect to the assessment of the both eutrophication and acidification of marine and terrestrial ecosystems. When emission threshold values are found for the agriculture and industry for the future decades a climate-chemistry setup like the current can be very useful. So far only the effects

from the anthropogenic emissions have been accounted for when these threshold values has been established. However, the current results show that it is important also to account for the impacts of climate change alone in the future.

Future outlook

This study is only in the beginning of an accelerating research field with respect to the impacts of climate change on air pollution. The main conclusions from the experiment described here is that it is scientifically sound to run a chemical transport model on climate data and that the temperature increase predicted by a great number of climate models seems to have a dominating effect on the future air pollution levels and distributions (see Hedegaard, 2007 and Hedegaard et al., 2008). This study has created a wide range of new hypotheses, which will be very interesting to study and test in the future.

From the current results it has become evident that the biogenic emission has a very large impact on the future air pollution distribution due to climate change. Currently the parameterisation of the natural VOC emitters in the DEHM model is only including isoprene. Terpenes are another group of VOCs, which are known to be released from biogenic sources as a function of temperature. The temperature dependent natural VOC emissions are composed of many contributions. Isoprene is known to produce ozone in contrast to terpenes, which are acting as a loss term for ozone. Therefore a sophistication of the biogenic emissions module in the model is one of the aims in the future.

Climate change affects air pollution. However, changes in air pollution levels of many species certainly also will affect the climate through for example contributing to the greenhouse effect or affecting the radiation balance in the atmosphere. So the ultimate aim in the future must be to establish a two-way coupled model system where feedback mechanism between air pollution and climate can exist.

References

Christensen, J. H., 1993, Testing Advection Schemes in a Three-Dimensional Air Pollution Model, <i>Mathematical and Computational Modelling</i>, 18 (2), pp. 75–88. Christensen, J. H., 1997, The Danish Eulerian Hemispheric Model – A three-dimensional air pollution model used for the Arctic, <i>Atmospheric Environment</i>, 31 (24), pp.4169–4191.	Frohn, L. M., J. H. Christensen and J. Brandt, 2002, Development of a High-Resolution Nested Air Pollution Model, <i>The Numerical Approach</i>, <i>Journal of Computational Physics</i>, 179 (1), pp. 68–94. Graedel, T.E., T.S. Bates, A.F. Bouwman, D. Cunnold, J. Dignon, I. Fung, D.J. Jacob, B.K. Lamb, J.A. Logan, G. Marland, P. Middleton, J.M. Pacyna, M. Placet and C. Veldt, 1993, A compilation

- of inventories of emissions to the atmosphere, *Global Biogeochem. Cycl.*, 7, pp.1–26.
- Guenther, A., C.N. Hewitt, D. Erickson, R. Fall, C. Geron, T. Graedel, P. Harley, L. Klinger, M. Lerdau, W. A. McKay, T. Pierce, B. Scholes, R. Steinbrecher, R. Tallamraju, J. Taylor and P. Zimmerman, 1995, A Global-Model of Natural Volatile Organic-Compound Emissions, *Journal of Geophysical Research - Atmosphere*, 100, pp. 8873–8892.
- Hedegaard, G. B., 2007, Impacts of climate change on air pollution levels in the Northern Hemisphere, NERI Technical Report, 240, National Environmental Research Institute, University of Aarhus, pp. 107.
- Hedegaard, G. B., J. Brandt, J. H. Christensen, L. M. Frohn, C. Geels and M. Stendel, 2008: "Modelling the impacts of climate change on air pollution levels in the Northern Hemisphere". *Atmospheric Chemistry and Physics*, 8, 3337–3367, 2008.
- Langner, J., R. Bergström and V. Foltescu, 2004, Impact of climate change on surface ozone and deposition of sulphur and nitrogen in Europe, *Atmospheric Environment*, 39, pp. 1129–1141.
- Murazaki, K. and P. Hess, 2006, How does climate change contribute to surface ozone change over the United States, *Journal of Geophysical Research.*, 111 (D05301).
- Olivier, J.G.J., A.F. Bouwman, C.W.M. van der Maas, J.J.M. Berdowski, C. Veldt, J.P.J. Bloos, A.J.H. Visschedijk, P.Y.J. Zandveld and J.L. Haverlag, 1996, Description of EDGAR Version 2.0: A set of global emission inventories of greenhouse gases and ozone-depleting substances for all anthropogenic and most natural sources on a per country basis and on 1 degree x 1 degree grid, RIVM report, TNO MEP report, R96/119, RIVM, Bilthoven.
- Roeckner, E., K. Arpe, L. Bengtsson, M. Christoph, M. Clausen, L. Dümenil, M. Giorgetta, U. Schlese and U. Schulzweida, 1996, The atmospheric general circulation model ECHAM-4: Model description and simulation of present-day climate, 218, Max-Planck-Institut für Meteorologie, Hamburg, Germany, pp. 167.
- Roeckner, E., L. Bengtsson and J. Feichter, 1999, Transient climate change simulations with a coupled atmosphere-ocean GCM including the tropospheric sulfur cycle, *Journal of Climate*, 12, Max-Planck-Institut für Meteorologie, Hamburg, Germany, pp. 3004–3032.
- Stendel, M., T. Schmidt, E. Roeckner and Ulrich Cubasch, 2002, The Climate of the 21st century: Transient simulations with a coupled atmosphere-ocean circulation model, Danish Climate Centre, 02-1, Copenhagen, Denmark, pp. 50.
- Tuovinen, J. -P., D. Simpson, P. Mayerhofer, V. Lindfors and T. Laurila, 2002, Surface ozone exposures in Northern Europe in changing environmental conditions. In: Hjort, J., F. Raes and G. Angeletti (eds), *A Changing Atmosphere: Proceeding of the 8th European Symposium on the Physico-Chemical Behaviour of the Atmospheric Pollutants*, European Commission, DG Research, Joint Research Centre, CD-ROM, Paper Ap6, pp.6.
- Vestreng, V., 2001, Emission data reported to UNECE/EMEP: Evaluation of the spatial distribution of emission, EMEP/MSC-W Note, 1/01.

Appendix 3 On the usage of an off-line chemistry transport model driven by a regional climate model to study air pollution and its impacts in the Nordic countries

Magnuz Engardt

Swedish Meteorological and Hydrological Institute, SE-601 76 Norrköping, Sweden, magnuz.engardt@smhi.se

Abstract

Climate change has the potential to change the concentration of most air pollutants through the coupling between meteorological variables on the one hand and atmospheric chemistry and physics on the other hand. In the present paper we report from our efforts to study the impact of climate change on air quality. Changes in tracer emissions or background concentrations are not discussed here.

Introduction (Present status within the topic)

Several processes determine the future loading of air pollutants in the Nordic countries. Important factors include changes in European precursor emissions, changes in the hemispheric background concentration of air pollutants, and changes in climate. Climate change can affect transport pathways, chemical and physical conversion rates and scavenging efficiencies. Climate change may also influence the atmospheric concentrations of air pollutants due to direct or indirect changes in emissions.

SMHI (the Swedish Meteorological and Hydrological Institute) pursues advanced climate modelling through the development, evaluation and application of a regional climate model operating on medium to high resolution over Europe. The latest version of the climate model (the

Rosby Centre regional Atmospheric climate model; RCA3) is described and evaluated in Kjellström et al.⁵.

To assess possible changes in air quality over Europe and the Nordic countries due to changes in climate we use the output from a regional climate model to drive a Eulerian off-line CTM (chemistry transport model) developed at SMHI.

SMHI has undertaken a number of studies on the coupling between climate-change and air quality over the last few years^{2,3,4,6,7}. In the following we give an overview of ongoing and planned work.

Results

In order to investigate the effects of climate change on air quality in Europe, we utilise our regional dispersion model, MATCH^{1,8}, forced with meteorology representing current as well as future climate conditions but keeping the emissions and boundary concentrations at their current value. The meteorology is from RCA3, the Rosby Center's regional climate model (covering the whole Europe on 50 km × 50 km resolution).

An investigation of the ability of the climate model to reproduce current meteorological conditions is, for example, given in Hole and Engardt⁴ and Langner et al.⁶.

Engardt and Foltescu³ shows that seasonal-mean ozone concentrations are expected to increase considerably (1–2% per decade up to 2050) in central and southern Europe, in particular during summer, following one climate change scenario. The daily maximum concentrations are expected to increase more than the daily mean concentrations. Northernmost Europe is projected to experience lower ozone concentrations under future climate, especially during spring and autumn. The increasing ozone concentrations will have a profound effect on a number of measures used to assess impacts on human health and vegetation. Figure 1 shows one example from Engardt and Andersson², where we compare the number of days exceeding 120 $\mu\text{g m}^{-3}$ during current and future climate. It is clear that those regions in Europe that already today experience ozone concentrations detrimental to human health can expect dramatic increases in ozone concentrations following changes in climate.

Figure 1. Number of days per year with daily-maximum 8-hour near-surface ozone concentration over land $>120 \mu\text{g m}^{-3}$. Left panel is current climate (1961-1990). Middle and right panels show the change from present climate to 2021-2050 and to 2071-100, respectively.

Hole and Engardt⁴ and Langner et al.⁶ investigated the deposition of acidifying and eutrophying nitrogen over the Nordic countries under future climate. They find that the deposition of reactive nitrogen over the Nordic countries is expected to change only little, except over the Norwegian coast where it will increase substantially due to anticipated increases in precipitation, see Figure 2.

Figure 2. Calculated change in atmospheric deposition of NO_y and NH_x to the Baltic Sea region following changes in climate. Relative change from 1961-1990 to 2021-2050 and to 2071-2100. Only changes significant at the 95% confidence level are indicated. Units: %.

Engardt and Foltescu³ show that the concentration of SIA will increase dramatically in continental Europe during all seasons except winter. The increase is largest around the Mediterranean during summer. The average summertime concentration of SIA will be 20% higher in 2021-2050 and 50% higher in 2071-2100 compared to current levels as a result of chang-

ing the meteorology (drier and warmer conditions in central and southern Europe). The increase in atmospheric SIA concentrations is related to a decrease in wet deposition of sulphur- and nitrogen containing species, which will be the consequence of climate change in large parts of central and southern Europe. Large areas around the Mediterranean, France, Belgium and the Netherlands will receive 50%, or less, of current nitrogen- and sulphur deposition in 2071–2100 compared to present.

The changed concentration and deposition patterns discussed above indicate that source receptor relations may change following altered deposition patterns and longer residence times of many species in the future atmosphere.

Discussion

Major uncertainties

Large uncertainties stem from the output of the regional climate models as they are constrained by the chosen CO₂-concentration scenario and the dynamics of their driving global climate model. Studies have shown that different global models on the boundaries of the regional climate model results in different regional climate.

To accurately model the concentrations of air pollutants in the future obviously also requires knowledge of future emissions and background concentrations of the tracers of interest as well as their precursors (including many short-lived oxidants). This typically requires coupling to global CTMs driven by global climate models and realistic emission scenarios.

Major challenges and future directions

Perform CTM simulations with climate data that spans the current uncertainty of regional climate simulations in Europe and thereby try to establish robust findings. It is also important to quantify the relative role of anticipated climate change in relation to changes in European emissions and changing hemispheric background. These relations will be different for different air pollutants.

Nordic perspective

The change in air quality in the Nordic countries due to changes in climate appears to be moderate although it will probably be substantial in south and central Europe. The uncertainties in the calculations are large and the risk for deteriorating air quality in the areas of the Nordic countries with the present highest impact, i.e. the southern and western Scandinavia should not be underestimated.

Conclusion

A number of studies have been performed by SMHI and other institutes to qualitatively assess the effect changing climate will have on a number of traditional air pollutants in Europe. They typically point towards substantial changes in south and central Europe but only small changes in the Nordic countries.

References

- ¹Andersson, C., J. Langner, R. Bergström. 2007. Interannual variation and trends in air pollution over Europe due to climate variability during 1958–2001 simulated with a regional CTM coupled to the ERA40 reanalysis. *Tellus* 59B, 77–98. doi: 10.1111/j.1600-0889.2006.00196.x
- ²Engardt, M., C. Andersson. 2008. European ozone in a future climate – modelling scenarios with a regional CTM coupled to regional climate data. Manuscript in preparation.
- ³Engardt, M., V. Foltescu. 2007. Luftföroreningar i Europa under framtida klimat. Swedish Meteorological and Hydrological Institute, SMHI Meteorologi Nr. 125, 62 pp. (In Swedish).
- ⁴Hole, L., M. Engardt. 2008. Climate change impact on atmospheric nitrogen deposition in Northwestern Europe: A model study. *Ambio* 37, 9–17.
- ⁵Kjellström, E., L. Bärning, S. Gollvik, U. Hansson, C. Jones, P. Samuelsson, M. Rummukainen, A. Ullerstig, U. Willén, K. Wyser. 2005. A 140-year simulation of the European climate with the new version of the Rossby Centre regional atmospheric climate model (RCA3), SMHI report, RMK No. 108, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden.
- ⁶Langner, J., C. Andersson, M. Engardt. 2009. Atmospheric input of nitrogen to the Baltic Sea basin: present situation, variability due to meteorology and impact of climate change. *Boreal Environment Research* (in press).
- ⁷Langner, J., R. Bergström, V. Foltescu. 2005. Impact of climate change on surface ozone and deposition of sulphur and nitrogen in Europe. *Atmos. Environ.* 39, 1129–1141.
- ⁸Robertson, L., J. Langner, M. Engardt. 1999. An Eulerian limited-area atmospheric transport model. *J. Appl. Meteor.* 38, 190–210.

Appendix 4 Enviro-HIRLAM: on-line coupled modelling of meteorological and atmospheric chemical transport processes with two-way feedbacks

Alexander Baklanov¹, Ulrik Korsholm¹, Allan Gross¹, Alexander Mahura¹, Bent Hansen Sass¹, Eigil Kaas²

[1] Danish Meteorological Institute, DMI, Research Department, Lyngbyvej 100, Copenhagen, DK-2100, Denmark (contacts: alb@dmu.dk)

[2] Niels Bohr Institute, University of Copenhagen, Juliane Maries vej 30, 2100 Copenhagen, Denmark

The strategy for developing new-generation online integrated Meteorology/Climate Model (MCM) and Atmospheric Chemical Transport Model (ACTM) systems (Figure 1), based on the HIRLAM/HARMONIE meteorological corner, is discussed on example of the online integrated Enviro-HIRLAM system (Baklanov, 2008, Baklanov et al., 2008; Korsholm et al., 2008) which is considered as the baseline system for the HIRLAM chemical brunch.

The integration/coupling of the RCM/NWP and ACT models could be realized by different ways using the online and offline modelling approaches. In more details the definition and specifics of the approaches, as well as the advantages and disadvantages of the online and offline modelling are described by Baklanov and Korsholm (2007) and in the WMO-COST report (2008). It could be realized using the following possible variants (see Figure 1):

One-way integration (offline coupling):

1. HIRLAM (or any other regional climate or NWP model) meteo-fields as a driver for ACTM (this way is traditionally used already by many air pollution modellers) (<—);
2. ACTM chemical composition fields as a driver for regional climate modeling or for NWP, e.g. HIRLAM (e.g. for aerosol forcing on meteo-processes) (--->).

Two-way integration:

1. Driver and partly feedbacks, for ACTP or for NWP (data exchange via an interface with a limited time period: offline or online access coupling, with or without second iteration with corrected fields) ($\Leftarrow \Rightarrow$);
2. ACTM is inside the HIRLAM model with full feedbacks included on each time step (online coupling) ($\Leftarrow \Rightarrow$).

Figure 1. Integrated Atmospheric System Model Structure.

Enviro-HIRLAM is an online coupled model for both short- and long-term simulations of both meteorological and chemical weather (Figure 2). It includes feedbacks, in the form of direct aerosol effects and the first and second indirect effects, between air-pollutants and meteorological processes.

Figure 2. Current version of the online integrated Enviro-HIRLAM modelling systems, showing the components of a forecast

The aerosol feedback mechanisms considering in the model are the following:

1. Direct effect - Decrease solar/thermal-IR radiation and visibility:
 - a. Processes involved: radiation (scattering, absorption, refraction, etc.);
 - b. Key variables: refractive indices, ext. coeff., SSA, asymmetry factor, AOD, visual range;
 - c. Key species: - cooling: water, sulfate, nitrate, most OC;
- warming: BC, OC, Fe, Al, polycyclic/nitrated aromatic compounds;
2. Semi-direct effect - Affect PBL meteorology and photochemistry:
 - a. Processes involved: PBL/SL, photolysis, meteorology-dependent processes;
 - b. Key variables: T, P, RH, Qv, WSP, WDR, Cld Frac, stability, PBL height, photolysis rates, emission rates of met-dependent primary species (dust, sea-salt, biogenic);
3. First indirect effect – Affect clouds drop size, number, reflectivity, and optical depth via CCN:
 - a. Processes involved: aerodynamic activation / resuspension, clouds microphysics, hydrometeor dynamics;

- b. Key variables: int./act. fractions, CCN size/compound, clouds drop size / number / LWC, COD, updraft velocity;
- 4. Second indirect effect - Affect cloud liquid water content, life-time and precipitation:
 - a. Processes involved: in-/below-cloud scavenging, droplet sedimentation;
 - b. Key variables: scavenging efficiency, precipitation rate, sedimentation rate.

Parameterisations of the aerosol feedback mechanisms in the Enviro-HIRLAM model is described in Korsholm et al. (2008).

The formation and transformations of atmospheric aerosols are known to be influenced by the dissolution of trace gases (if wetted), nucleation, condensation, evaporation and coagulation. Therefore, the aerosol module in Enviro-HIRLAM comprises two parts:

- a thermodynamic equilibrium model (NWP-Chem-Liquid) and
- an aerosol dynamics model.
- For simulating aerosol dynamics 3 models has been implemented, covering both sectional and modal approaches:
 - - the modal aerosol module from the Chemistry-Aerosol-Cloud (CAC) model developed at DMI (Gross and Baklanov, 2004),
 - - the sectional Model for Simulating Aerosol Interactions and Chemistry (MOSAIC) (Zaveri et al., 2007) and
 - - the Modal Aerosol Dynamics Model for Europe (MADE) (Ackermann et al., 1998) with the secondary organic aerosol model (SORGAM) (Schell et al., 2001).

Note that only the implementation of the CAC aerosol model has been tested so far.

As it was shown in WMO-COST (2008) integrated models overview at the current stage most of the online coupled meso-scale models do not consider feedback mechanisms or include only direct effects of aerosols on meteorological processes (like COSMO LM-ART and MCCM). Only two meso-scale on-line integrated modelling systems (WRF-Chem and Enviro-HIRLAM) consider feedbacks with indirect effects of aerosols.

Possible applications of the online integrated Enviro-HIRLAM modelling system include the following:

- chemical weather forecasting,
- air quality and chemical composition longer-term assessment,
- weather forecast (e.g., in urban areas, severe weather events, etc.),
- pollen forecasting,
- climate change modelling (Enviro-HIRHAM),

- studies of climate change effects on atmospheric pollution on different scales,
- volcano eruptions, dust storm, nuclear explosion consequences,
- other emergency preparedness modelling.

Current progress in the Enviro-HIRLAM system development and its on-line coupled modelling applications are considered. Several sensitivity tests of off-line versus on-line coupling in Enviro-HIRLAM at DMI as well as verification versus experiments are considered and results are discussed. Enviro-HIRLAM has been employed in two case studies of the importance of urban aerosol feedbacks (i) for the region of northern Europe; and (ii) for the metropolitan area of Paris. Results are presented and discussed.

Advantages and disadvantages of on-line integration in comparison with, the more common, off-line coupling of MCMs and ACTMs are mentioned using Enviro-HIRLAM as a specific example. The way of online integration modeling considering feedback mechanisms is more promising for the future and could be beneficial for model improvements in both communities: Climate-Meteorology and Atmospheric environment / Chemical weather forecasting.

Brief overview of the future research plans within the HIRLAM community and the new European 7FP project MEGAPOLI: Megacities: Emissions, Impact on Air Quality and Climate, and Improved Tools for Mitigation Assessments (see *Nature*, 2008, vol. 455, 142–143), coordinated by DMI, is also presented.

References:

- Ackermann, I. J., H. Hass, M. Memmesheimer, A. Ebel, F. S. Binkowski, and U. Shankar, 1998, Modal aerosol dynamics model for Europe: Development and first applications, *Atmos. Environ.*, 32, No.17, 2981–2999.
- Baklanov A., 2008: Integrated Meteorological and Atmospheric Chemical Transport Modeling: Perspectives and strategy for HIRLAM/HARMONIE, *HIRLAM Newsletter*, 53: 68–78.
- Baklanov, A. and U. Korsholm: 2007: On-line integrated meteorological and chemical transport modelling: advantages and prospective. In: Preprints ITM 2007: 29th NATO/SPS International Technical Meeting on Air Pollution. Modelling and its Application, 24 – 28.09.2007, University of Aveiro, Portugal, pp. 21–34.
- Baklanov A., U. Korsholm, A. Mahura, C. Petersen, A. Gross, 2008: ENVIRO-HIRLAM: on-line coupled modelling of urban meteorology and air pollution. *Advances in Science and Research*, 2: 41–46.
- Gross, A., Baklanov A., 2004: Modelling the influence of dimethyl sulphide on the aerosol production in the marine boundary layer, *International Journal of Environment and Pollution*, 22(1/2): 51–71.
- Korsholm, U.S., A. Baklanov, A. Gross, A. Mahura, B.H. Sass, E. Kaas, 2008: Online coupled chemical weather forecasting based on HIRLAM – overview and prospective of Enviro-HIRLAM. *HIRLAM Newsletter*, 54: 1–16.
- Schell B., I.J. Ackermann, H. Hass, F.S. Binkowski, and A. Ebel, 2001, Modeling the formation of secondary organic aero-

solved within a comprehensive air quality model system, *Journal of Geophysical Research*, 106, 28275–28293.

WMO-COST, 2008: Baklanov, A., B. Fay, J. Kaminski, R. Sokhi: Overview of existing integrated (off-line and on-line) meso-scale systems in Europe. Joint Report of COST728 and GURME, May 2007. WMO-COST publication. GAW Report No. 177. WMO TD No. 1427.

Available also from:

<http://www.cost728.org>

Zaveri, R. A., R. C. Easter, J. D. Fast, and L. K. Peters, 2007, Model for simulating aerosol interactions and chemistry (MO-SAIC). *J. Geophys. Res.*, doi:10.1029/2007JD008782.

Appendix 5 Climate forcing of aerosols with heterogeneous chemical composition and complex internal structure

Michael Kahnert and Valentin Foltescu

Swedish Meteorological and Hydrological Institute, SE-601 76 Norrköping, Sweden

Background

There is increasing interest in the role of aerosols in the climatic system. Aerosols are considered one of the least understood factors influencing radiative budget of the terrestrial atmosphere. (Forster et al., 2007).

The interaction of atmospheric aerosols with solar radiation is of paramount importance in two major disciplines of atmospheric research: i) remote sensing and ii) climate

change research. In remote sensing of aerosols one aims at retrieving information about the distribution and physico-chemical properties of the aerosols from observed radiances. In climate research, on the other hand, one needs to quantify the impact of aerosols on radiative fluxes based on information about their distribution in the atmosphere. In either case a sufficiently accurate optical model of the aerosol scattering and absorption properties is required.

Most aerosol species counteract to some extent the positive forcing of the greenhouse gases and black carbon aerosols. The net direct effect of the total aerosol range from -0.9 to -0.1 W/m^2 on global average. Recent findings (as outlined in the next section dealing with research at SMHI and elsewhere) indicate that the level of scientific understanding of the direct aerosol forcing may be lower than previously assumed.

Most GCMs seem to underestimate the positive forcing effect of soot. Jacobson (2001) found that internal mixing of BC with other species could increase the positive forcing by as much as a factor of two. Subtracting a two small smaller quantity from the generally negative net direct forcing of the remaining aerosol components appears into an exaggerated overall negative direct forcing of aerosols which most likely is not valid.

IPCC (Forster et al., 2007) points out the following sources of error while estimating the aerosol forcing:

- representation of size distribution
- treatment of aerosol chemistry
- hygroscopicity and water adsorption
- parameterisation of sea salt and wind-blown dust generation
- vertical mixing and removal processes influencing vertical distribution of aerosols
- radiative transfer computations

Aerosols in nature can also often have complex morphologies. Some types of aerosols can have non-spherical or rough surfaces, such as mineral dust particles. Others, such as soot and fly ash aerosols, typically consist of clusters of particles. Anthropogenic aerosols in polluted air masses often consist of inhomogeneous internal mixtures of different chemical compounds. The morphology effects are generally not considered in today's climate models. However, it has long been recognised that particle shape is one of the most important parameters in developing accurate remote sensing retrieval methods (Mishchenko et al., 1997).

Accumulating evidence suggests that the mixing state (Jacobson, 2001) and shape (Kahnert and Kylling, 2004; Kahnert et al., 2007) of aerosols are equally important for accurately quantifying climate forcing by particles. Due to their complex internal structure it is particularly challenging to investigate the interrelation of chemical, physical, optical, and radiative properties of chemically heterogeneous, internally mixed aerosols, and to develop and test robust remote sensing retrieval and climate forcing models for such particles.

Activities at SMHI

SMHI has been involved in basic research on the direct aerosol effect for the last 4 years. Today's set-up is that the MATCH model (Multiple-Scale Atmospheric Transport and Chemistry) developed at SMHI supplies information on chemistry, dynamics, thermodynamics and removal of aerosols. Mixing ratios, $dN/d\log r$ and soon also the dynamically calculated mixing state make up the driving data for aerosol optics and radiative transfer calculations. The effective medium theory, EMT is used to calculate refractive indexes of the internally mixed aerosol. EMT presents an approximation to estimate the optical properties of an inhomogeneous particle by its substitution with a homogeneous particle having an effective refractive index. With this input, numerical methods in electro-

magnetic scattering theory are employed to calculate the aerosol optics variables:

- extinction cross section, averaged over aerosol population
- extinction optical depth
- averaged single scattering albedo (the fraction of total extinction due to scattering)
- averaged asymmetry parameter
- averaged Mueller matrix (determining the angular distribution of the scattered intensity and polarisation)

The above quantities are fed into radiative transfer calculations which deliver the spectral radiance and the spectral radiative flux.

In an external mixture mapping from mixing ratios to optical properties is linear and the computations are rather simple. In an internal mixture the mapping is non-linear, making it more difficult to generate pre-computed look-up tables. This leads to a computationally demanding task if internal mixture is to be considered in the future climate models.

The degree of difficulty and sophistication in the electromagnetic scattering calculations increase when other model particles are considered rather than homogeneous spheres. Inhomogeneous/irregular particles require e.g. discrete dipole approximation (Draine and Flatau, 1994), or finite-difference time domain method (Yang et al., 2000). Clusters of spheres can be handled by coupled-cluster T-matrix (Mackowski and Mishchenko, 1996).

Point-group symmetries can be modelled with T-matrix (Kahnert, 2004). High-order Chebyshev particles as well as homogeneous spheroids can also undergo T-matrix calculation (Rother et al., 2006; Mishchenko, 1991). Coated sphere and homogeneous sphere can be solved for with analytic solution (Toon and Ackerman, 1981; Mie, 1908).

Figure 1 gives evidence from the significance of morphology for aerosol forcing rates. It presents the outcome of a Swedish-Finnish study (Kahnert, Nousiainen and Räisänen, 2007).

The figure displays errors in radiative fluxes related to the treatment of aerosol optical properties. The y-axis refers to the net flux on the top of the atmosphere (TOA), a key parameter for the large-scale tropospheric temperature field. The figure displays 3 normalized net radiative flux errors for 5 types of nonspherical mineral aerosols.

The black bars show the normalized net flux errors related to uncertainty in “ m ”, the refractive index, based on computations for spherical particles.

The red and the blue bars represent the net radiative flux errors caused by the spherical particle approximation (SPA) in flux calculations as compared to the laboratory measured proxies for two extreme refractive indexes, “ m_1 ” and “ m_2 ”.

Figure 1. Normalized spectral net flux errors at TOA for five aerosol samples at a wavelength of 441.6 nm and a surface albedo of 0.1.

The conclusion of this study is that the use of spherical model particles can introduce errors comparable to those related to the uncertainty in the refractive index, which is often regarded as being the largest source of errors.

Research at SMHI (Kahnert et al., 2007) and elsewhere (e.g. Veihelmann et al., 2006; Nousiainen et al., 2006) support the use of spheroidal model particles for non-spherical particles in aerosol optical calculations. Spheroidal particles could significantly reduce errors in estimates of the direct radiative forcing of at least mineral aerosols.

In the remote sensing community we have such an acceptance that observational networks start assuming spheroidal model particles in operational remote sensing applications.

In addition to the climate forcing calculations, SMHI is performing atmospheric transmission modelling to supplement remote sensing. Figure 2 shows profiles of aerosol backscattering coefficient measured by the lidar instrument of the Defence Research Institute (FOI) in Linköping and computed by MATCH.

In summary, particle shape is one of the most important factors in developing accurate aerosol retrieval methods (e.g. Mishchenko et al., 1997). It has been conjectured that the discrepancy between predicted and observed direct radiative effects of aerosols may be related to morphological effects not accounted for in the models (Chandra et al., 2004).

Mixing state and shape are equally important for accurately quantifying climate forcing by aerosols (e.g. Jacobson, 2001; Kahnert et al., 2007).

Figure 2. Backscattering coefficient as measured by lidar and calculated by the MATCH model.

Yet, not only mixing state, but also shape of non-spherical particles have been consistently neglected in climate modeling. It is still common to employ the homogeneous sphere approximation for estimating the direct radiative forcing for aerosols. SMHI will continue its strive to provide new insights into the significance of different morphological particle properties in aerosol climate forcing simulations, and to provide both error estimates and specific recommendations for suitable model particles that can be employed for achieving aerosol direct forcing estimates with substantially increased accuracy.

References

- Chandra, S, Satheesh, SK, and Srinivasan, J (2004). *Geophys. Res. Lett.* 31, doi:10.1029/2004GL020662.
- Draine, BT and Flatau, PJ (1994). *J. Opt. Soc. Am. A* 11, 1491.
- Forster, P, Ramaswamy, V, Artaxo, P, et al., in: Solomon, S, Qin, D, Manning, M, et al. (Eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, 2007.
- Jacobson, MZ (2001). *Nature* 409, 695.
- Kahnert, M, and Kylling, A (2004). *J. Geophys. Res.* 109, doi:10.1029/2003JD004318.
- Kahnert, M (2004). *J. Quant. Spectrosc. Radiat. Transfer* 85, 231.
- Kahnert, M, Nousiainen, T, and Veihelmann, B (2005). *J. Geophys. Res.* 110, doi:10.1029/2004JD005558.

- Mackowski, DW and Mishchenko, MI (1996). *J. Opt. Soc. Am. A* 13, 2266.
- Mishchenko, MI (1991). *J. Opt. Soc. Am. A* 8, 871.
- Mishchenko, MI, Travis, LD, Kahn, RA, et al. (1997). *J. Geophys. Res.* 102, 16,831.
- Nousiainen, T, Kahnert, M, and Veihelmann, B (2006). *J. Quant. Spectrosc. Radiat. Transfer* 101, 471.
- Rother, T, Schmidt, K, Wauer, J, et al. (2006). *Appl. Opt.* 45, 6030.
- Veihelmann, B, Nousiainen, T, Kahnert, M, et al. (2006). *J. Quant. Spectrosc. Radiat. Transfer* 100, 393.

Appendix 6 Future human and vegetation exposure for ozone - European emissions, hemispheric background, climate change and local geography

Karlsson, P.E¹, Pleijel, H.², Pihl Karlsson, G.¹, Klingberg, J.², Piikki, K.^{2,3}, Tang, L.⁴ Chen, D.⁴

1Swedish Environmental Research Institute (IVL), P. O. Box 5302, SE-400 14, Göteborg, Sweden; 2Department of Plant and Environmental Sciences, University of Gothenburg, P. O. Box 461, SE-405 30, Göteborg, Sweden; 3School of Life Sciences, University of Skövde, P. O. Box 408, SE-541 28, Skövde, Sweden; 4Earth Science Centre, University of Gothenburg, P.O. Box 460, SE-405 30, Göteborg, Sweden

Abstract

The factors that influence the human and vegetation exposure for ozone in northern Europe are complex and many are potentially sensitive to climate change. European emissions of ozone precursors are expected to decrease while hemispheric background ozone concentrations appear to increase. Ozone levels over Fennoscandia are strongly influenced by long-range transport and hence synoptic weather patterns. However, ozone levels near the ground are also depending on local climatology, in particular air turbulence during night-time. This is in turn strongly depending on local geographical settings such as local topography. Climate change is usually considered at very large geographical scales. However, climate change at the local scale may also be important for local ozone levels.

Regional ozone levels

European emissions of ozone precursors are expected to decrease in the nearest future¹, even though we have not yet in northern Europe seen the expected decrease in the high ozone levels. At the same time hemispheric background ozone levels are increasing^{2,3}, which in part may counteract European emission reductions. The net result of these changes for ozone

levels in northern Europe remains to be established and will probably depend on latitude.

Clearly the synoptic weather patterns are important for long-range transport of ozone precursors as well as for photochemistry⁴. Lamb Weather Types (LWT) can be used for a daily classification of synoptic weather patterns. A careful analysis of ozone measurements at three sites in southern Sweden over the period 1990-2005 showed that the occurrence of ozone episodes may be correlated with certain LWTs⁵. This confirmed the strong influence of synoptic weather patterns on the occurrence of high ozone levels and may be potentially useful for ozone episode predictions. A special case of the influence of background ozone is the high ozone levels during spring. Ozone levels in Fennoscandia are particularly high during the spring months March-May⁶, when meteorological conditions favour ozone formation, even when trajectory analysis indicates that the air originates from far northern latitudes, i.e. the Arctic. We would expect this air to be relatively clean. However, the maximum 8-h mean ozone concentrations can under these conditions exceed 50 ppb, all over Sweden.

Local ozone concentrations near the ground

There can be considerable differences in ozone levels near the ground in relatively small geographical distances⁷. Air quality standards for ozone are frequently exceeded at the coastal EMEP ozone monitoring station at Råö, approximately 30 km south of Gothenburg, while exceedences are far less frequent at the inland ozone monitoring station at Östads Säteri, approximately 45 km north-east of Gothenburg⁸. Hence, it is important to understand which geographical area that a certain ozone monitoring site represents. The ozone concentration near the ground result from the balance between the deposition towards the ground- and vegetation surfaces and the supply of ozone from aloft. Consequently, ozone concentrations are very sensitive to air turbulence and vertical transport⁹. During conditions with night-time air temperature inversions, that impede vertical ozone transport, ozone concentrations near the ground may decrease to very low levels and during the morning hours it takes some time before ozone again reaches regional levels. The occurrence of these conditions depends on the synoptic weather patterns and the geographical settings for the site¹⁰. A position far from the coast and large lakes as well a position low in the local topography all favour the occurrence of low night-time ozone concentrations. Hence, it is suggested that within a certain region there may be areas close to the coast and/or positioned high in the local topography that have a relatively larger risk for high ozone levels, while inland areas positioned low in the local topography may have a

lower risk. The importance of this classification will depend also on the frequency of clear summer nights under anti-cyclonic weather conditions.

Trends in local ozone and meteorology in west Sweden

Climate change is usually considered at very large geographical scales. However, local climate changes may be very important for local ozone levels. Hourly ozone and meteorological data at Östads Säteri were available for the periods 1993–1995 and 2003–2007. An analysis showed a substantial increase in the mean daytime ozone concentrations for the month of September for the period 2003–2007, as compared to 1993–1995. A similar comparison of meteorological parameters showed that daytime air temperatures for September were higher and daytime wind-speed lower during the latter period. Furthermore, the dominant wind direction had changed from northerly to southerly. Daytime ozone concentrations at Råö for September did not seem to have increased in the same way between the two periods. Thus, it seems that warmer and slower, more southerly winds, i.e. conditions more favourable for ozone formation, may explain the increasing daytime ozone concentrations in September at Östads Säteri. We are not yet in a position to claim that this is the result of climate change, since the dataset and the time period is too small. However, it illustrates how a local climate change might influence local ozone levels.

Discussion

Major uncertainties

Ozone levels in northern Europe are under the influence of two large-scale changes: reductions of European ozone precursor emissions and increasing hemispheric background concentrations. The net result of these changes for ozone levels and exceedences of air quality standards remains to be established.

In particular the high elevation mountain region in northern Fennoscandia is influenced by background ozone levels and it is unfortunate that there is at present no regular ozone monitoring station operating in this area at an altitude above 1000 m a.s.l.

It is important to understand the cause behind the high spring ozone levels in air originating from northern latitudes, in what we would consider as relatively “clean air”. Is it due an anthropogenic accumulation of ozone precursors during the Arctic winter or is it due to inclusion of stratospheric ozone?

Major challenges and future directions in a Nordic perspective

The problem of groundlevel ozone in northern Europe differs to that of continental and southern Europe in many ways. Ozone levels in northern Europe depend mainly on long-range transport and the influence of local emissions is small. Ozone is more influenced by background ozone levels in northern as compared to southern Europe. The humid climate promote leaf ozone uptake through the stomata (see document by Pleijel et al.), which means that the relative impacts of a certain air concentration of ozone on the vegetation will be larger in northern Europe as compared with e.g. the dry climate conditions in much of the Mediterranean region¹¹. Also, epidemiological studies indicates surprisingly large influence of ozone on human health in northern Europe. If the European abatement of ozone precursors was to only be based on ozone indices that are calculated from air concentrations, then all efforts would most likely be focussed on reducing the very high ozone concentrations in continental and southern Europe. Hence, it is very important to establish dose-modifying factors both for the ozone impacts on vegetation but also most likely for the ozone impacts on human health.

References

- ¹ Solberg, S., Bergström, R., Langner, J., Laurila, T., Lindskog, A., 2005. Changes in Nordic surface ozone episodes due to European emission reductions in the 1990s. *Atmospheric Environment* 39, 179–192.
- ² Simmonds, P.G., Derwent, R.G., Manning, A.L., Spain, G., 2004. Significant growth in surface ozone at Mace Head, Ireland, 1987–2003. *Atmospheric Environment* 38, 4769–4778.
- ³ Karlsson, P.E., Tang, L., Sundberg, J., Chen, D., Lindskog, A. and Pleijel, H. 2007. Increasing risk for negative ozone impacts on vegetation in northern Sweden. *Environmental Pollution* 150, 96–106.
- ⁴ Andersson, C., Langner, J. and Bergström, R., 2006. Inter-annual variation and trends in air pollution over Europe due to climate variability during 1958–2001 simulated with a regional CTM coupled to the ERA40 reanalysis. *Tellus* 59B, 77–98.
- ⁵ Tang, L., Deliang Chen, Per Erik Karlsson, Yongfeng Gu, Tinghai Ou. Synoptic circulation and its influence on spring and summer surface ozone concentrations in southern Sweden. Submitted to *Boreal Env. Res.*
- ⁶ Monks, P.S. 2000., A review of the observations and origins of the spring ozone maximum. *Atmospheric Environment* 34, 3545–3561.
- ⁷ Sundberg, J., Karlsson, P.E., Schenk, L., Pleijel, H. 2006. Variation in ozone concentration in relation to local climate in south-west Sweden. *Water, Air & Soil Pollution* 173, 339 – 354.
- ⁸ Karlsson, P.E., Pleijel, H., Danielsson, H., 2004. Marknära ozon, SO₂, NO₂ och sot vid Östads Säteri 1987–2003. IVL Report B1556. (in Swedish)
- ⁹ Coulter, R.L. 1990. A case study of turbulence in the stable nocturnal boundary layer. *Boundary-Layer Meteorology* 52, 75–91.
- ¹⁰ Fowler, D., Smith, R.I., Coyle, M., Weston, K.J., Davies, T.D., Ashmore, M.R. & Brown, M. 1995. Quantifying the fine scale exposure and effects of ozone. *Water Air and Soil Pollution*, 85, 1479–1484.
- ¹¹ Simpson, D., Ashmore, M., Emberson, L., Tuovinen, J.-P. 2006. A comparison of two different approaches for mapping potential ozone damage to vegetation. A model study. *Environmental Pollution*, 146, 715–725.

Appendix 7 Global change and plant ozone uptake: Impact of elevated CO₂ and meteorology

Pleijel, H.¹, Karlsson, P.E.², Uddling, J.¹, Klingberg, J.¹, Piikki, K.^{1,3}, Pihl Karlsson, G.² and Danielsson, H.²

¹*University of Gothenburg, Plant and Environmental Sciences, P.O. Box 461, SE-405 30 Göteborg, Sweden, håkan.pleijel@dpes.gu.se; ²Swedish Environmental Research Institute (IVL), P. O. Box 5302, SE-400 14, Göteborg, Sweden; ³University of Skövde, School of Life Sciences, P.O. Box 408, SE-541 28 Skövde, Sweden*

Abstract

Tropospheric ozone is probably the most important gaseous pollutant for effects on vegetation on a regional-global scale. It is also important for health effects and as a greenhouse gas. Global change involves several potential changes that may strongly influence ozone exposure. There are rising trends for background ozone, also in the Nordic region. Ozone uptake by vegetation is strongly modified by air and soil humidity, CO₂ concentration and temperature. A warmer, humid climate in combination with a longer growing season and a higher ozone background would enhance ozone uptake by vegetation, while dryer conditions and elevated CO₂ tend to reduce ozone uptake. Since ozone effects on plant are closely related to ozone uptake, risk assessment for ground-level ozone is very sensitive to the local, specific pattern of environmental change. In the Nordic climate an increasing future potential for ozone effects seems to be rather likely although uncertainties are large in this assessment.

Introduction

Tropospheric ozone is today considered the most important gaseous pollutant for effects on vegetation. It is also very important for health effects and as a greenhouse gas. Locally, other pollutants may be more important, but the large-scale occurrence pattern for ozone makes a major threat among air pollutants to agriculture, forestry and other vegetation types. Rising trends for background ozone have been observed in different parts of the world, including the Nordic region¹, and there is evidence of significant intercontinental transport of ozone and its precursors.

Effects of ozone are not related to ozone concentration in a simplistic manner. There are dose-modifying factors which have to be taken into account in risk assessment. Research during the last fifteen years has shown that ozone effect on plants are more strongly correlated with ozone uptake through the stomata (small pores on the leaves that regulate the gas exchange of plants) than with the ozone conditions prevailing exterior to the leaves^{2,3}. Important dose-modifying factors include meteorological factors like vapour pressure deficit (VPD), temperature (T) solar radiation and soil moisture. Incorporation the effect of these factors into the exposure index for ozone has lead to strong dose-response relationships between effects observed in experiments performed in different European countries and ozone exposure⁴. Furthermore, phenological aspects are of large importance. The duration of the vegetation period, which is strongly related to temperature, delimit the period during which ozone uptake takes place. An additional dose-modifying factor, with strong links to climate change, is the CO₂ concentration. At higher CO₂ concentration plants tend to reduce their stomatal conductance⁶. Thereby the water use efficiency, the amount of carbon fixed in the photosynthesis in relation to the amount of water vapour lost, of the plant is improved.

The aim of this text is to shortly review the current understanding of the global change factors that modify ozone uptake and the potential effect on vegetation in a future with an altered climate. Emphasis is given to the specific conditions in the Nordic countries.

Results – dose-modifying factor related to plant ozone uptake

Vapour pressure deficit - VPD

A high VPD represents a high evaporative demand through plant transpiration, water vapour loss from the leaves. If the transpiration rate is very high, the plant tissue will tend to dry out, and in the end wilt if water cannot not be delivered from the root to the shoot at a sufficient rate. Thus, at high VPD the plants will tend to close their stomata to reduce the transpiration. Stomatal closure will also reduce ozone uptake.

In the Nordic climate VPD is generally low or rather low and does not represent an important limitation to stomatal conductance. However, ozone episodes, which mostly occur in anticyclonic weather conditions, are sometimes, but not always, associated with rather high VPD, which will tend to limit ozone uptake.

Soil moisture

Similar to the point raised for VPD, limitation of water availability in the soil will tend to reduce the stomatal conductance in order to avoid water depletion of the plants. This can have a profound effect on ozone uptake. This was shown already in the 1980s in ozone*soil moisture experiments in North America. There are also examples showing much larger ozone effects on irrigated fields compared to non-irrigated adjacent fields after strong ozone episodes, such as in Greece.

Compared to many other climates of the world, soil moisture is much less limiting to vegetation in the Nordic climate, but sometimes there are droughts which will influence stomatal conductance significantly and thus ozone uptake.

It can be noted in this context that ozone concentrations were very high in large parts of Europe (but not that much in the Nordic region) during the dry summer of 2003. The dry conditions (low soil moisture, high VPD) probably lead to a reduced stomatal conductance and thus a limitation of ozone uptake. Since ozone deposition to plants is a major mechanism for removal of ozone, ozone concentrations may have been significantly higher in the summer of 2003 than if vegetation uptake would have been larger, resulting in higher human exposure to ozone⁶.

Temperature

Temperature influences plant development, but also gas exchange may be influenced. At low to moderate temperatures, it represents limitation to gas exchange. Thus increasing temperatures may lead to higher ozone uptake in the Nordic climate. Very high temperatures may limit gas exchange. Such high temperatures are very rare in northern Europe. The temperature effect on stomatal conductance needs further study.

Phenology

The duration of the vegetation period is often defined in terms of the continuous period with a daily temperature average exceeding a certain temperature (e.g. 4°C). There are strong indications that the vegetation period is becoming longer, thus permitting ozone uptake for large part of the year. This is of particular importance for the northern part of the Nordic region. In this area there is often a pronounced spring peak in ozone, which is rather high in some years. Until recently, much of this peak has occurred before the vegetation period starts. With earlier onset of spring in the north the risk is larger that this spring ozone peak will influence vegetation¹.

Carbon dioxide

The fact that carbon dioxide tends to promote stomatal closure has been shown in many investigations. For example, in the EU programme CHIP, where the effects of CO₂, O₃ and other stresses on potato were studied there was a reduction in stomatal conductance by doubling ambient [CO₂] in the range of 10-20%, with the higher value for higher absolute conductance levels⁷. In a Swedish experiment with wheat, an even larger effect by doubled CO₂ was observed⁸. It has to be noted that elevated CO₂ also tends to promote growth and alter growth patterns. In both potato and wheat⁹, it has been observed that the yield stimulation by elevated CO₂ is expressed in terms of a larger number of tubers/grains, while yield reduction by ozone is mostly linked to a smaller size of tubers/grains. Furthermore, and of large importance for CO₂ effects on long-lived vegetation such as forest, there is evidence from large-scale experiments with high ecological realism that long-term effects of CO₂ on forests may not result in any significant reduction in stomatal conductance, and thus not in a protection against ozone and also not in an increased water runoff as has been predicted by models using data from smaller scale short-term experiments¹⁰.

Discussion

Major uncertainties

The most important uncertainty in the assessment of future effects of ozone on plants is the pattern of change in climate and ozone levels. Although there is a good understanding of the way different global change drivers (T, VPD, soil moisture, CO₂) affect plants and their ozone uptake, the quantification of the relevant processes should be improved.

Major challenges and future directions

In addition to further study of mechanisms related to plant gas exchange and response, a major challenge in this research field is to integrate the understanding of these mechanisms into atmospheric models. In this way improved assessment of potential future changes in ozone and CO₂ effects on vegetation can be achieved.

Nordic perspective

Different models do not provide identical message in terms of the most likely changes in the Nordic climate in the present century. There seems, however, to be strong indications that a significantly warmer and more humid (perhaps not in summer but in spring) climate is likely to prevail.

The growing season is then going to be much longer and any limitation of temperature on stomatal conductance will be reduced. Further study is needed to assess the potential future impact of VPD and soil moisture on stomatal conductance, but unlike certain other parts of the world, drought may not become a very important feature in the Nordic climate in a global change perspective.

Unlike some strongly polluted areas further south in Europe where reduced local emissions are highly important for ground-level ozone, the ozone concentrations in the Nordic region are strongly influenced by the large-scale background. The combined trends for ozone and expected climate change in the Nordic countries are likely to increase the risk for ozone effects on vegetation.

A special element of risk exists in the far north, where the nights during the growing season are short or non-existent. The dark period represents a recovery from oxidative stress imposed on the plants not only by ozone, but also by light and side effects of the photosynthesis. This can make the plants in this climate especially sensitive to increasing oxidative stress by elevated background ozone concentrations in combination with higher temperatures giving rise to higher stomatal conductance and prolonged period of ozone uptake.

Conclusion

The combined trends for ozone and expected climate change in the Nordic countries are likely to increase the risk for ozone effects on vegetation, with some particular problems of the northern part of the region. If VPD becomes higher or soil moisture lower this conclusion may turn out to be incorrect. A increasing threat of ozone to vegetation could also to some extent be mitigated by rising CO₂ concentrations, but the effect of CO₂ on plant conductance, especially in long-lived vegetation such as forest, is uncertain and needs further study.

References

- ¹ Karlsson PE, Tang L, Sundberg J, Chen D, Lindskog A, Pleijel H. 2007. Increasing risk for negative ozone impacts on vegetation in northern Sweden. *Environmental Pollution* 150, 96–106.
- ² Pleijel H, Danielsson H, Pihl Karlsson G, Gelang J, Karlsson PE, Selldén G. 2000. AN ozon flux-response relationship for wheat. *Environmental Pollution* 109, 453–462.
- ³ Pleijel H, Danielsson H, Ojanperä K, De Temmerman L, Högy P, Badiani M, Karlsson PE. 2004. Relationships between ozone exposure and yield loss in European wheat and potato – a comparison of concentration- and flux-based exposure indices. *Atmospheric Environment* 38, 2259–2269.
- ⁴ Pleijel H, Danielsson H, Emberson L, Ashmore M, Mills G. 2007. Ozone risk assessment for agricultural crops in Europe: Further development of stomatal flux and flux-response relationships for

- European wheat and potato. *Atmospheric Environment* 41, 3022–3040.
- ⁵ Ainsworth EA, Rogers A. 2007. The response of photosynthesis and stomatal conductance to rising [CO₂]: mechanism and environmental interactions. *Plant, Cell and Environment* 30, 258–270.
- ⁶ Solberg S, Coddeville P, Forster C, Hov Ø, Orsolini Y, Uhse K. European surface ozone in the extreme summer 2003. *Atmos. Chem. Phys. Discuss.* 5, 9003–9038.
- ⁷ Pleijel H, Danielsson H, Vandermeiren K, Blum C, Colls J, Ojanperä K. 2002. Stomatal conductance and ozone exposure in relation to potato tuber yield – results from the European CHIP programme. *European Journal of Agronomy* 17, 303–317.
- ⁸ Uddling J, Gelang-Alfredsson, Karlsson PE, Selldén G, Pleijel H. 2008. Source-sink balance of wheat determines responsiveness of grain production to increased [CO₂] and water supply. *Agriculture, Ecosystems and Environment* 127, 215–222.
- ⁹ Piikki K, De Temmerman L, Ojanperä K, Danielsson H, Pleijel H. 2008. The grain quality of spring wheat (*Triticum aestivum* L.) in relation to elevated ozone uptake and carbon dioxide exposure. *European Journal of Agronomy* 28, 245–254.
- ¹⁰ Uddling J, Teclaw RM, Kubiske ME, Pregitzer KS, Ellsworth DS. 2008. Sap flux in pure aspen and mixed aspen-birch forests exposed to elevated concentrations of carbon dioxide and ozone. *Tree Physiology* 28, 1231–1243.

Appendix 8 Transport of short-lived pollutants into the Arctic, and why it is important for climate

Andreas Stohl, Kjetil Tørseth, John Burkhart, Sabine Eckhardt, David Hirdman, Harald Sodemann

Norwegian Institute for Air Research, Instituttveien 18, 2027 Kjeller, Norway, ast@nilu.no

With contributions from many others outside NILU

Abstract

We will present case studies as well as climatologies of air pollution transport into the Arctic and discuss its potential role for climate change in the Arctic. In particular, we will present two cases of transport of smoke from biomass burning events, where we can show that not only the concentrations of many short-lived pollutants in the air were enhanced but that the albedo of the snow was also affected by the deposition of soot. The presentation will be based on three recent papers (1, 2, 3).

References

- ¹ Stohl, A., T. Berg, J. F. Burkhart, A. M. Fjæraa, C. Forster, A. Herber, Ø. Hov, C. Lunder, W. W. McMillan, S. Oltmans, M. Shiobara, D. Simpson, S. Solberg, K. Stebel, J. Ström, K. Tørseth, R. Treffeisen, K. Virkkunen, K. E. Yttri (2007): Arctic smoke – record high air pollution levels in the European Arctic due to agricultural fires in Eastern Europe. *Atmos. Chem. Phys.* **7**, 511–534.
- ² Stohl, A., E. Andrews, J. F. Burkhart, C. Forster, A. Herber, S. W. Hoch, D. Kowal, C. Lunder, T. Mefford, J. A. Ogren, S. Sharma, N. Spichtinger, K. Stebel, R. Stone, J. Ström, K. Tørseth, C. Wehrli, and K. E. Yttri (2006): Pan-Arctic enhancements of light absorbing aerosol concentrations due to North American boreal forest fires during summer 2004. *J. Geophys. Res.* **111**, D22214, doi:10.1029/2006JD007216.
- ³ Stohl, A. (2006): Characteristics of atmospheric transport into the Arctic troposphere. *J. Geophys. Res.* **111**, D11306, doi:10.1029/2005JD006888.