Research in support of Air Pollution Policies

Results from the first phase of the Swedish Clean Air and Climate Research programme

Final report

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Swedish Clean Air and Climate Research Program
Frisk luft och Klimat

FORSKNING FÖR MILJÖMÅLEN
NATURVÅRDSVERKETS FORSKNINGSANSLAG

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Results from the first phase of the Swedish Clean Air and Climate Research programme

Final report

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Förord

Naturvårdsverket förvaltar ett anslag för miljöforskning till nytta för Naturvårdsverket samt för Havs- och vattenmyndigheten. Föreliggande rapport “Results from the first phase of the Swedish Clean Air and Climate Research programme” utgör en avrapportering från ett forskningsprogram som har haft stöd från detta anslag.

Resultaten från programmet är ett viktigt stöd för Naturvårdverkets internationella arbete i EU och FN:s luftvårdskonvention samt för arbetet med uppföljningen av våra nationella miljökvalitetsmål. Programmet har bland annat bidragit med viktig kunskap gällande kostnadseffektivitet för åtgärdsstrategier mot utsläpp av klimatpåverkande luftföroreningar, sambanden mellan luftföroreningar och hälsoeffekter, ozonpåverkan på skogstillväxt och luftföroreningarnas påverkan på klimatet i Arktis. Det svenska och internationella luftvårdsarbetet har traditionellt varit ett nära samarbete mellan forskning och policy. Resultaten som presenteras i denna rapport kommer att utgöra viktiga inspel till det fortsatta arbetet för ren luft i Sverige och i Europa.

Stockholm 30 oktober 2017

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Summary

The overall objective of the Swedish Clean Air and Climate Research Programme (SCAC) financed by the Swedish Environment Protection Agency (SEPA) is "To develop and improve the scientific basis for air pollution policies on national and international scales". The present report summarizes the key findings of the Phase 1 of the programme (November 2013 – March 2017).

The program has been successful in generation new knowledge in several areas for direct importance for both national and international policy. The international part covers results to be implemented within the CLRTAP, the EU and the Arctic Council. Some of the key findings are listed below:

- A Scandinavian version of the GAINS model was developed, by which it is possible to optimize costs for air pollution measures with respect to the main pollutants and SLCPs. (WP1)
- The choice of climate metric shows surprisingly little impact on the relative cost effectiveness of SLCP abatement measures in Sweden, even if including variation in climate metric values for the SLCPs. (WP1)
- Current and future needs for national emission projections and scenarios were analysed as well as roles and responsibilities in the present system. Based on the analysis needs for changes have been identified. (WP2)
- Systematic sensitivity analysis could improve the understanding and quantification of projections and it was shown how sensitivity analyses in emission projections and scenarios could be undertaken, taking different objectives into account. (WP2)
- High-resolution dispersion models were developed for the three urban domains Göteborg, Stockholm and Umeå with respect to the most important source categories of particle emissions; traffic exhaust, road traffic non-exhaust, residential wood combustion, shipping and other activities. (WP3)
- A new methodology was developed to calculate highly resolved (time and space) ozone concentrations without the need to use advanced photochemical modelling. The method was used to assess impact of ozone on pregnancy outcomes. (WP3)
- Exposure data for 1990–2011 on PM_{10}, $PM_{2.5}$ and BC for the three urban areas were applied to several cohorts, and dose response-functions were calculated for cardiovascular disease, lung function as well as pregnancy outcomes. The most consistent evidence for cardiovascular effects was observed for BC and stroke with a hazard ratio of 1.14 per µg m^{-3}. For lung function, data from Gothenburg showed small but statistically significant reductions related to all three types of particles from road traffic. In a study in Stockholm it was also shown that exhaust particle exposure was associated with small birth weight; the odds ratio increase during the first trimester was 1.09 per 200 ng m^{-3}. (WP3)

- Model calculations show that emission changes in Europe affect Arctic climate. Model simulations indicate that the Arctic has warmed by 0.5 K since 1980's due to sulphur emission reductions over Europe. Further, by 2050, a reduction of global aerosol emissions from fossil fuels could lead to a global and Arctic warming of 0.3 K and 0.8 K respectively, compared to 2005. (WP4)
- The contribution from different sectors and pollutants to Arctic temperature change has been studied by using the RTP concept. However, analyses of robustness of the concept show less agreement for the Arctic, an issue to be further investigated. (WP4)
- Future ozone impacts on human health and ecosystems will depend more on chronic exposure to medium rather than high peak concentrations. (WP4)
- In order to evaluate ozone effects on tree growth and carbon sequestration, a database on annual stem growth has been established for Norway spruce, Scots pine and European beech at 25 different forest observation sites in southern part of Sweden. Statistical analysis of the data is presently ongoing. (WP4)
- The present understanding of dynamic effects to ecosystems from nitrogen deposition was evaluated through an international workshop. (WP4)

Sammanfattning

Den övergripande målsättningen med Naturvårdsverkets forskningsprogram SCAC *Clean Air and Climate Research Programme* är att utveckla och förbättra den vetenskapliga basen för nationella och internationella luftvårdsåtgärder. Föreliggande rapport sammanfattar de viktigaste resultaten från den första fasen av programmet (november 2013 – mars 2017).

Inom programmet har vi tagit fram ny kunskap inom flera områden av direkt betydelse för både nationell och internationellt luftvårdsarbete. Internationellt har resultaten varit av betydelse för Luftvårdskonventionen (CLRTAP), EU och Arktiska Rådet. Nationellt har resultaten direkt betydelse för flera av miljökvalitetsmålen. Några av de viktigaste resultaten sammanfattas i det följande:

- En skandinavisk version av den så kallade GAINS-modellen har utvecklats med vilken det är möjligt att kostnadsoptimera luftvårdsåtgärder med avseende på de viktigaste luftföroreningarna och de kortlivade klimatpåverkande luftföroreningarna. (SLCP) (WP1)
- Valet av klimatindikator (t ex GWP 100) visar sig ha förvånansvärt liten betydelse för kostnadseffektiviteten hos åtgärder riktade mot SLCP i Sverige. (WP1)
- Det nuvarande och framtida behovet av officiella utsläppsprognoser och scenarier har analyserats liksom fördelningen av roller och ansvar. Baserat på analysen har behovet av förbättringar identifierats.
- Systematisk känslighetsanalys kan förbättra förståelsen och de kvantitativa uppskattningarna hos utsläppsprognoser och i projektet har vi visat hur känslighetsanalyser kan utföras genom att ta hänsyn till olika mål för prognoserna. (WP2)
- Högupplösta spridningsmodeller har utvecklats för de tre urbana områdena Göteborg, Stockholm och Umeå med avseende på partikelemissioner från de viktigaste källtyperna, trafikavagser, icke avgasbundna partiklar, vedeldning för lokaluppvärmning, fartygstrafik och övriga aktiviteter. (WP3)
- En ny förenklad metodik har utvecklats för beräkning av högupplösta (tid och rum) ozonkoncentrationer utan att använda avancerad fotokemisk modellering. Metoden användes för att analysera effekten av ozon på graviditetsutfall. (WP3)
- Exponeringsdata för 1990–2011 för PM_{10}, $PM_{2.5}$ och BC för de tre urbana områdena applicerades på flera kohorter och dos-responssamband beräknades för hjärt-kärlsjukdomar, lunkfunktion och graviditetsutfall. De mest konsistenta resultaten för hjärtkärlsjukdomar observerades för sot (black carbon, BC) i relation till stroke med en riskkvot på 1.14 per µg m^{-3}. När det gäller lungfunktion visade data från Göteborg en liten men statistisk signifikant reduktion med avseende på alla tre partikeltyperna från vägtrafik. I en studie i Stockholm visades dessutom att exponering för avgaspartiklar kunde relateras till låg födelsevikt. (WP3)

- Modellberäkningar visar att emissionsförändringar i Europa har signifikant påverkan på klimatet i Arktis. De visar bl.a. att Arktis har blivit 0.5 grader varmare sedan 1980 till följd av svavelåtgärderna i Europa. Resultaten visar vidare att en global minskning av partikelutsläppen från fossila bränslen till 2050 kan leda till ytterligare uppvärmning som globalt uppskattas till 0.3 grader globalt och till 0.8 grader över Arktis jämfört med 2005. (WP4)
- Betydelsen av olika sektorer och föroreningar för temperaturförändringarna i Arktis har studerats med användning av RTP-konceptet. Beräkningarna visar dock på en sämre överenstämmelse för Arktis, en fråga som behöver studeras ytterligare. (WP4)
- För framtida påverkan från ozon på hälsa och ekosystem kommer kronisk exponering för måttligt förhöjda halter att bli viktigare än episoder med höga halter. (WP4)
- För att utvärdera ozons effekter på trädtillväxten och inbindningen av kol har en databas utvecklats med avseende på den årliga stamtillväxten hos gran, tall och bok. (WP4).

Introduction

The Swedish Environmental Protection Agency (SEPA) has for many years supported national air pollution research in order to improve the scientific basis for national and international air pollution policies. This research includes in particular the Swedish Clean Air Research Program (SCARP) http://www.scarp.se/ and the Climate change and Environmental Objectives research program (http://www.cleoresearch.se/). The most recent of these programs, the Swedish Air and Climate Research Program SCAC (http://www.scac.se/), for which we here present the final report for Phase 1, was initiated in November 2013 and its first phase ended in March 2017. The program had a budget of 25 MSEK and involved nine Swedish research groups and one international partner[1]. The SCAC program was organized in four work packages:

- Integrated Assessment Modelling (IAM) – Synergies and Conflicts (WP1)
- Air Pollution Projections and Scenarios (WP2)
- Health Effects from Air Pollution (WP3)
- Climate and Ecosystems Effects (WP4)

The program is, with respect to national policies, mainly directed to four of the SEPA's 16 Environmental Quality Objectives; Clean Air, Reduced Climate Impact, Zero Eutrophication and Natural Acidification Only. With respect to Reduced Climate Impact, it is mainly focussed on short lived climate pollutants.

For international policies, the program's main end-users are the Convention on Long-range Transboundary Air Pollution (CLRTAP) and the European Union. Since the impact of air pollution on Arctic climate has been a task of the program, the Arctic Council has also become a policy body of interest for our results.

[1] IVL Swedish Environmental Research Institute, (IVL); Karolinska Institutet (KI); Swedish Meteorological and Hydrological Institute (SMHI); Stockholm University (SU); Gothenburg University (GU); Stockholm Air Quality and Noise analysis, City of Stockholm (SLB); Umeå University (UmU); Lund University (LU); International Institute for Applied System Analysis (IIASA)

Program Objectives

The overall objective of the Swedish Clean Air and Climate Research Program (SCAC) is:

> *To develop and improve the scientific basis for air pollution policies on national and international scales.*

More precisely we have defined the following objectives:

- Develop tools and systems analysis approaches for combined cost-effective abatement of Swedish air pollution and Short Lived Climate Pollutants (SLCP) and considering long lived GHG. (WP1)
- Develop systematic methodologies and processes for air pollution emission projections and scenarios, given various climate and energy policies, and taking into account future policy needs and requirements. (WP2)
- Improve the robustness of Swedish air pollution emission projections and estimates of emission abatement potentials in particular for shipping, agriculture and industries (including EU-ETS). (WP2)
- Develop and validate methods for estimating respirable particulate levels, such as black carbon (BC) from different sources with appropriate time and spatial resolution to be used in epidemiological studies and health impact assessments. (WP3)
- Develop sector distributed air pollution projections and exposure-response functions for long-term exposure to respirable particulates (such as BC) from different sources with respect to morbidity and identify suitable health indicators. (WP 2 and WP3)
- Make health impact assessments and cost estimates focusing on case studies including scenarios for reducing exposures. (WP3)
- Estimate the direct and indirect radiative forcing (RF) of different, cooling and warming, short-lived climate forcers for N Europe and the European Arctic. (WP4)
- Translate the radiative forcings from Short-Lived Climate Pollutants (SLCPs) into surface temperature change. (WP4)
- Estimate the indirect effects of ground level ozone on RF and on forest growth and carbon sequestration in N Europe. (WP4)
- Evaluate and suggest further development of concepts and methods for describing critical loads and ecosystems effects. (WP4)

The program has focused on existing concepts and modelling tools applied in air pollution policy development, negotiations and assessments, with emphasis to incorporate new and improved scientific knowledge on human exposure and health effects, ecosystem exposure and effects, synergies and conflicts for air pollution and climate abatement including SLCP and robust systems and processes for emission projections and scenarios.

The program activities have often been linked to a number of other research activities supported by other organisations, in particular European Union, Nordic Council of Ministers and national research councils. Significant additional financial support will be mentioned under each work package.

The Work Package 1 Integrated Assessment Modelling (IAM) has served as a cross-cutting activity through which research activities and results were synthesized. The programme and the four WPs covered all the main topics originally set out in the call for proposal.

Achievements WP 1: Integrated Assessment Modelling (IAM) – Synergies and Conflicts

Key overarching research questions

- Which technical and non-technical measures are available and will they be sufficient to reach national climate and air quality objectives?
- What are the discrepancies between results obtained with the GAINS model using different health and climate indicators and those from more topic-specific models? Do these discrepancies influence cost efficient abatement strategies obtained by GAINS? Which further developments would be needed to increase the applicability and robustness of the GAINS model?
- Which are the best tools and strategies to reach co-beneficial and cost effective abatement strategies in Sweden for a better air quality and reduced climate change 2030 and 2050?

Background to the SCAC work with IAM

On the 18th of December 2013, the European Commission proposed a Clean Air Policy Package, setting out objectives and abatement measures for 2030. The package included proposals for a creation of a Medium Combustion Plant (MCP) Directive (European Commission 2013a), EU Council acceptance of the amendment to the 1999 Protocol of the Air Convention (European Commission 2013b), and an amendment to the National Emissions Ceilings (NEC) Directive (European Commission 2013c). These proposals would together help the EU countries reduce the adverse environmental and human health impacts associated with emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), non-methane volatile organic compounds (NMVOC), fine particulate matter ($PM_{2.5}$), and methane (CH_4).

The proposal was supported by impact assessments (European Commission 2013d) using integrated assessment modelling, primarily the IIASA GAINS model (Amann et al. 2011a, Kiesewetter et al. 2015). For the first time in a European air pollution policy context the ambition level of a proposal was based on a cost-benefit analysis (CBA) (Amann et al. 2014). In other words, the proposal was based on model estimates of which European emission levels that would be optimal for society, given projected economic activity in polluting sectors. One way to interpret this new approach to air pollution policy is that the Commission now implicitly assumes that it is possible to identify an optimal future air pollution level, where both emission control needs as well as and health and environmental benefits can be fully expressed in economic terms. This assumption is made despite the fact that the scientific and policy communities are aware that there are many aspects not included in the analysis.

GAINS is today used to support a large number of air pollution and climate policy initiatives by showing which control options that are cost efficient to reach suggested policy ambition levels. Examples of these initiatives are the Multi-pollutant, Multi-effect (Gothenburg) protocol of the Air Convention (Amann et al. 2011b), the European Commission proposal for A Clean Air Programme for Europe and National Emissions Ceilings (NEC) Directive (European Commission 2013c), and the EU GHG effort sharing decisions (AEA 2012).

The analytical framework behind the Cost Effectiveness Analysis (CEA) and CBAs used by the Air Convention and within the EU is regularly reviewed. Applications of IAM such as GAINS always have the objective to provide results based on best available knowledge at the time of the analysis. With this dynamic approach to develop the model in line with new knowledge and improvement in model design and performance there is a constant need for reviewing the robustness of these models. New knowledge might lead to substantially different model outcomes, (e.g. novel findings on health effects from exposure to NO_2) with shifts in both ambition levels and preferred technological choices, while other new findings (e.g. more detailed knowledge about health effects from exposure to $PM_{2.5}$) will only lead to minor changes and only have impacts on ambition levels.

The answers from IAM calculations show the decision makers not only which the desirable future emission level is, but also in which country, sector and with which control options that emissions should be controlled. The results are used to guide policy efforts directed towards certain sectors and can also be used to give support on whether international collaboration or domestic action is preferable. It is therefore important to always ensure that the models are fit for their purposes and also give the best outcome.

For the further development of new air pollution policy it is also important to verify to what extent past actions have been successful. There are many drivers of air pollution emission reduction and knowledge about successes and failures in undertaken measures are important as a basis for further actions. Is it worthwhile to continue strengthening air pollution policy or will changes happen ‘autonomously’ or via other policies? One policy area with significant impact on air pollution emissions is climate policy. The often strong link between emissions of CO_2 and air pollutants has been brought forwards as a rationale for integrating climate and air pollution policies. However, one effect of this link is also that it has been taken as an excuse for focusing entirely on CO_2 and expecting that the climate policy will also do the job for air pollution. This has been the case at least since the first version of the NEC directive was initiated. During the years prior to 2001, there were discussions to hold off a NEC directive since the EU commitments under the Kyoto Protocol were expected to reduce also emissions of air pollutants. A similar story evolved around 2006–2007 when the NEC directive underwent its first revision attempt.

This revision was postponed with arguments that air pollution would be largely dealt with through the upcoming new EU Climate & Energy package (EU 20/20/20). The same argument was used again in December 2014 when the European Commission planned to modify the proposal for an amendment of the NEC directive with the motivation that the proposal was: "*To be modified as part of the legislative follow-up to the 2030 Energy and Climate Package.*" (European Commission, 2014). In other words, there have been situations when the Commission has argued that dedicated air pollution policy was superfluous in comparison to strengthened climate policies.

In SCAC we have used the decision support tools used in European air pollution managing processes and analysed to what extent certain parameters could have an impact on the perceived cost-effectiveness of emission control.

Method

In this report we present three specific research activities done within WP1. The methods differed with respect to the specific research questions asked.

The first piece of research is an analysis of which Swedish SO_2 policy instruments that were most successful in reducing SO_2 emissions. This research also has policy relevance since it implicitly shows whether SO_2 policy was significant in Sweden during a time when Sweden simultaneously made large efforts to reduce GHG emissions. To answer these questions we applied decomposition analysis (Hoekstra and van der Bergh 2003) based on data between 1990 and 2012. Our decomposition analysis is based on Rafaj et al. (2014), but we disaggregated the analysis into separate calculations for the Energy & Transport and the Industrial Processes sectors. In combination with the decomposition analysis we made an inventory on the development of Swedish SO_2 policies over the years and identified correlations between emission reductions and policy developments.

In a second part of our research, we studied the robustness of SLCP emission control costs with respect to the climate metric used to calculate the climate impact of the control. Given that most control of SLCP emissions have to small climate impact to be directly modelled, the use of climate metrics such as Global Warming Potential (GWP) or Global Temperature Potential (GTP) are necessary. There is however no consensus on which measure to use, and different studies often use different metrics. In the literature different metrics have different meanings, and the choice of which metric to use is value-based (Tanaka et al. 2014). The choice of metric will have an impact on the relative importance of whether it is most cost effective to reduce emissions of long-lived greenhouse gases or short-lived. However, there are no studies on to what extent the choice of climate metric has an impact on the relative cost effectiveness of options that reduce emissions of different short lived climate pollutants (BC, CH_4, NO_x, NMVOC). In SCAC we have studied this question by using an inventory of available technical options in Sweden and assessed their respective climate impact with the use of the most common climate metrics and time spans found in the literature (Myhre et al. 2013).

Finally we have as the third item of our research used the GAINS model to study if different actor perspectives (social planner and corporate perspectives) will have a substantial impact on which control options that are perceived as most cost effective. We used a Nordic version of the model that allows for the use of different interest rates and depreciation periods when calculating control costs. By calculating cost optimal emission abatement control for the Nordic countries for different interest rates we could identify potential impacts of actor perspectives on which technology that would be preferred.

Results achieved so far

The decomposition analysis showed that even in Sweden, where many emission control measures were implemented between 1970 and 1990, dedicated SO_2 policy measures introduced after 1990 have had a substantial impact on SO_2 emission trends. Although structural changes of the economy have been most important, dedicated SO_2 policy have been responsible for 26% of the decoupling of emissions from economic growth. (Figure 1)

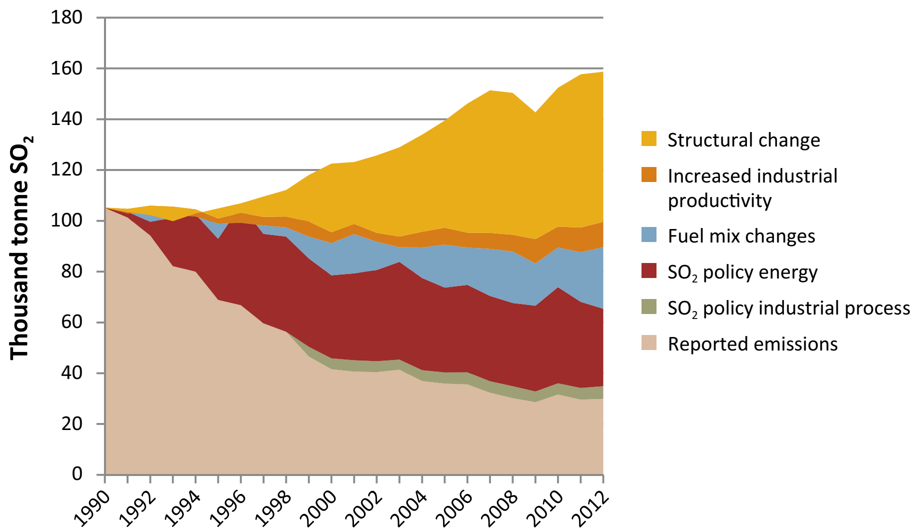

Figure 1: Driving forces of SO_2 emission reduction in Sweden 1990–2012. Dedicated SO_2 policy was responsible for 35 ktonne of the decoupling of SO_2 emissions from economic growth. 35 ktonne corresponds to 26% of the total decoupling and 58% of the emission reduction from 1990.

On the control of SLCPs, our study showed that the choice of climate metric have generally a relatively small impact on the relative climate cost effectiveness of the studied SLCP control options (Figure 2). The most important deviation was the control options that implied NO_x emission reductions, given the large temporal variation in estimated climate impacts from NO_x. The choice of climate metric had a large impact on the relative climate cost effectiveness of NO_x control.

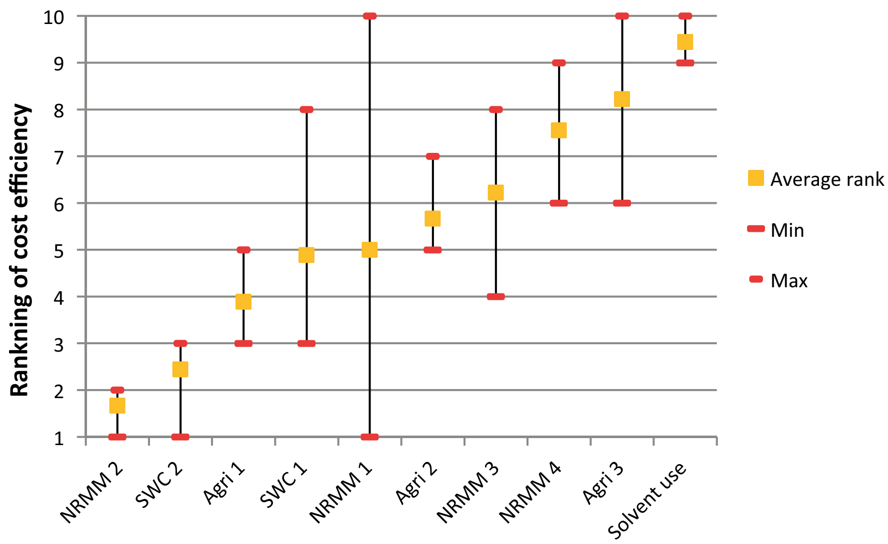

Figure 2: The average, min and max relative rank in cost efficiency of 10 SLCP control options in Sweden. The rank of each option was calculated with different climate metrics for the pollutants considered. The option NRMM 1 mainly controls NOx emissions and is therefore sensitive to the choice of climate metric.

The preliminary results from our analysis of how actor perspectives might influence technology choice showed that for some, but not all ambition levels, the perspective will have a relatively large impact (Figure 3). For a 35% gap closure ambition level by 2030, the corporate perspective might increase socio-economic costs in the Nordic countries with 12 million € / year (41%). For an 85% gap closure, the corporate perspective would imply cost increases with 105 million € / year (37%) in the model analysis. For example, our analysis shows that the corporate perspective promotes large investments in control of Danish $PM_{2.5}$ emissions from small scale wood combustion as a cost optimal solution, whilst the social planner perspective does not.

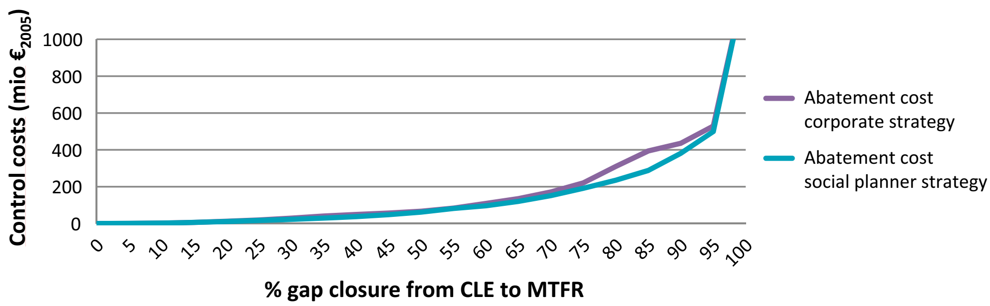

Figure 3: Preliminary results showing the socio-economic costs of further (above legislation) control of Nordic $PM_{2.5}$, SO_2, NO_x emissions in 2030 when choosing technologies as deemed cost optimal by a social planner or as deemed cost optimal from a corporate perspective.

The results from SCAC WP1 are not yet delivered but the manuscripts will be submitted for publication shortly.

Deliverables from WP 1

D1.1	Manuscript: *The impact of Swedish SO_2 policies on SO_2 emissions 1990–2012*, to be submitted
D1.1	Research application: *Communication of Uncertainty in Scientific Decision Support in the Context of Climate Change*, submitted 15th of March 2016
D1.2	Working paper / IVL report: *Conceptual Framework of how to incorporate Non-technical measures into Integrated Assessment Models*, to be delivered
D1.3	Preliminary results from GAINS Scandinavia phase I: *Analysing potential drivers of high air pollution abatement costs – the importance of perspectives*, to be submitted
D1.3	Preliminary results from GAINS Scandinavia phase II and III: *Analysis of simultaneous cost effective emission reductions at sea and at land, a model study applied to the Nordic region*, to be submitted
D1.3	IVL Technical PM: *Swedish marginal costs of NO_x emission reduction in 2030 in the European Commissions' NEC scenario*, PM delivered to Swedish EPA 2017-04-05
D1.4	IVL Technical PM: *Possibilities and problems with analysing cost efficient greenhouse gas and air pollution emission abatement in GAINS Scandinavia*, forthcoming
D1.5	Manuscript: *Climate metric impacts on cost efficiency ranking of air pollution abatement strategies*, to be submitted to Climate Policy

Comments to the results

The decomposition analysis shows that even in a country like Sweden with ambitious climate policies since 1991, directed SO_2 policy achieved at least 58% of the SO_2 emission reduction 1990–2012. Furthermore, the sensitivity analysis showed that *if* the Swedish fuel mix had remained constant over the period 1990–2012, dedicated SO_2 policy had been responsible for an even larger share of the emission reduction from 1990. In other words, dedicated SO_2 policy has functioned as a safe guard for SO_2 emission reduction over the period.

The calculations of the cost effectiveness of SLCP control options appear to be relatively stable regardless of which climate metric used to calculate the cost effectiveness from a climate perspective. The major exception from this general conclusion is SCLP control options that include control of NO_x emissions.

The actor perspective might for some policy ambition levels have a clear impact on which technologies that are considered as most cost effective. Given that investment decisions are made mostly with economic perspectives other than the social planners' these preliminary results indicate a need for sensitivity analysis in coming cost calculations.

Implications for air quality policy development

The results from the decomposition analysis give support for continued work with air quality policy, in contrast to allowing air pollution policy to be considered only as a part of climate policy.

Policies for reducing climate impacts of air pollution do not need to be impeded by the academic discussion about which climate metric to use and when.

The analysis of most suitable combination of emission abatement should include sensitivity analysis of the impacts of interest rates chosen when calculating emission abatement costs.

If looked at from the perspective of what these results means for the cost-efficient solution in a CBA, our results show that:

a) It is still relevant to analyse costs of air pollution control in relation to air pollution benefits as stand-alone from other drivers of emission reductions. Even though direct air pollution control is not responsible for all emission reductions, the impact appears large enough to support analysis separate from analysis of combined air pollution and climate change control costs.

b) Analyses of cost effectiveness of SLCP control need not be too concerned with the choice of climate metric with the exception of NO_x control. The choice of climate metric will mainly have an impact on the relative importance of SCLP or CO_2 emission control. The cost optimal technology choice is not largely affected.

c) The choice of actor perspective might however have a significant impact on the cost optimal technology choice. Further analyses are required but the preliminary results indicate a need for sensitivity analysis on cost perspectives in future IAM analysis.

Communication activities from WP1

Where	When	Context	Target group	Title
Boulder, Colorado, United States	June 2014	GEIA conference	Researchers	Poster: Swedish legislation impact on acid deposition – Focus on Sweden in 1990–2010
Rochester, NY State, United States	October 2015	Acid Rain 2015	Researchers and policy makers	Presentation: Evidence-based impact of SO_2-policies 1990–2012? – A case study applied to Swedish Emission inventory data
Göteborg, Sweden	February 2017	SCAC Final Conference	Researchers and policy makers	Presentation: How robust are the objectives for air quality in the future? In Swedish

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Achievements WP2: Emission projections and scenarios

WP 2.1–2.3 Swedish processes for emission projections and scenarios

Background

National emission projections and scenarios play an important role in developing international, national and regional policies and measures to reduce the release of greenhouse gases and air pollutants to the atmosphere. For example, national air pollutant projections are used for assessing the progress towards national and regional environmental objectives, and for validating the IIASA baseline scenarios which are used as policy support in international negotiations within EU and CLRTAP (Åström et al., 2013).

The present Swedish system for preparation of national projections of air pollution and greenhouse gas emissions is primarily developed to facilitate regular reporting to EU, CLRTAP and the UNFCCC following mandatory reporting requirements (UNECE, 2014; UNFCCC, 2000; EC, 2013). It is mainly based on the Swedish ordinance for greenhouse gas emission reporting (SFS 2014:1434) but needs to be coordinated with the overall process for developing national projections also for air pollutants.

Developing national emission projections is a complex process based on cooperation between several governmental agencies and other organisations (see Figure 4). Presently, projection development is not fully based on the understanding of the need from end-users. The task to coordinate the different actors and information management falls on the Swedish EPA according to the national ordinance.

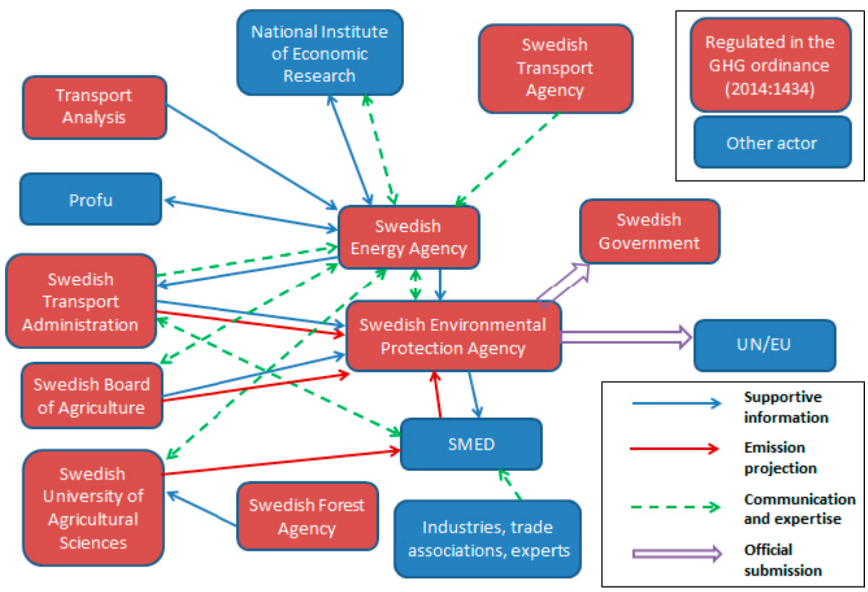

Figure 4. Some important governmental agencies and other organizations participating in the Swedish emission projection system for air pollutants and greenhouse gases.

The emission projections, underpinned by models and other assumption on future developments, are associated with a fairly large degree of uncertainty. Improved understanding of the factors behind the projected emissions, such as GDP development, future demand on energy and transport, technological development, etc., could reduce the uncertainty in emission projections, improve legitimacy of the outcome and provide enhanced support in decision making processes.

The aim of this WP was to develop a conceptual approach for preparing robust, systematic, flexible and harmonized national emission projections of greenhouse gases and air pollutants that are useful also for other purposes than to fulfil reporting obligations to the EU and UN. One obvious use of improved emission data is their implementation in air quality and climate models at various temporal and spatial scales. Furthermore, the credibility of emission projections hinges on present-day verification.

Much of the ideas and conclusions in this work were developed in close cooperation with a reference group consisting of a number of relevant national stakeholders (Swedish Environmental Protection Agency, Swedish Energy Agency, Statistics Sweden, Swedish Meteorological and Hydrological Institute, County Administrative Board of Västra Götaland, Swedish Transport Administration). The theoretical framework is derived based on some key references, such as Börjesson et al. (2006) on scenario types and techniques, and Pannell (1997) regarding strategies for sensitivity analysis in a broad sense.

Results

The overall result of the work is a conceptual approach in the form of a user's guide for implementing an emission projection system for multiple users and purposes. Below is an overview of the systematic questions in the user's guide, further elaborated in Gustafsson & Kindbom, 2017.

1. Who is interested in emission projections and for what purposes?
   a. Conduct a stakeholder analysis and a needs analysis
2. What organization and skills are needed?
   a. Identify actors and knowledge needed
   b. Include all relevant actors from the start
   c. Define and designate roles and responsibilities; maintain high flexibility
3. What does a well-organised work process look like?
   a. Let the needs govern/dictate the processes
   b. Coordinate project management for air pollutants and greenhouse gases
   c. Active project management
   d. Establish working teams to enable good communication and cooperation
   e. Keep everyone updated through meetings and communication
   f. Clarify best practice in choosing data sources, methods, models and assumptions

   g. Ensure quality assurance and quality control in all steps of the process and for all actors
   h. Use sensitivity analyses as a tool throughout the entire process
   i. Make well-founded priorities
   j. Learn from previous experiences
4. How to collect and produce data?
   a. Base the work on the international framework and guidelines
   b. Define terminology and scoop
   c. Use previous experiences as a basis
   d. Focus on key issues
   e. Be consistent in the implementation of assumptions
   f. Ensure transparent and accessible documentation of data sources, assumptions, methods, models, etc.
5. How to communicate the results and to whom?
   a. Customize the results and message
   b. Use sensitivity analyses to convey messages

In working with the conceptual approach an evaluation of the present Swedish emission projection system was performed. To produce projections in a resource efficient manner, ensure useful results, and improve the understanding and communication of future projections, a number of key recommendations were developed (Gustafsson & Kindbom, 2017):

- Important stakeholders and other relevant actors in Sweden should together discuss the needs, use and priorities of emission projections
- Coordinate the preparation of air pollutant and greenhouse gas emission projections, both from national and regional perspectives
- Strengthen the cooperation and communication between relevant actors
- Improve the accessibility and documentation of produced projections
- Coordinate the assumptions on future development
- Use sensitivity analyses for improved understanding, communication and priorities
- Improve the process for evaluation and feedback

The recommendations are further elaborated in Gustafsson & Kindbom (2017) and are exemplified below:

The initial analysis of needs (Kindbom & Gustafsson, 2015) identified lack of coordination during preparation of air pollution and greenhouse gas emission projections as a common and important problem. This could be exemplified by how the projection of residential use of biomass for heating is treated differently depending on the purpose. As particle emissions associated with residential wood combustion can have a large impact on human health (as presented in WP3), projections on future biomass is of high importance when developing air pollution reduction strategies. However, the national energy projections are developed to fulfil the reporting obligations of the greenhouse gas emission projections, for which future residential biomass use is not an important factor. This leads to less robust projections for the emissions of particulate matter, due to lack of coordination and priority of resources between the preparation of air pollution and greenhouse gas emission projections.

Sensitivity analysis could be a useful tool for improved understanding, communication and priority-setting in the emission projections system (Kindbom & Gustafsson, 2017). One example of the importance of sensitivity analysis in decision-making is a study from the County Administrative Board of Västra Götaland. Scenarios were used for evaluation of future NO_2 concentrations in ambient air in projected housing areas, in relation to environmental quality standards. Two scenarios were available for the evaluation; one reference scenario and one "worst-case" scenario (Figure 5). During the evaluation, the County Administrative Board recognized that the "worst-case" scenario did not accurately represented all underlying uncertainties, and that important decisions had to be made based on limited and uncertain background information. The conclusion was that sensitivity analyses developed based on user needs could reduce the uncertainty in decision making.

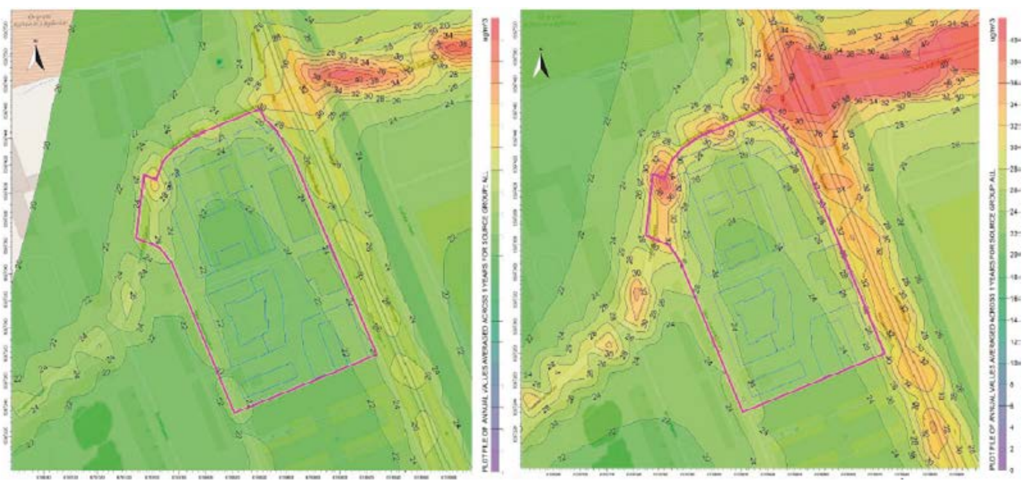

Figure 5. NO_2 concentration scenarios for 2020 for a projected housing area in Gothenburg. Left figure shows the reference case and the right figure a "worst-case" scenario. Both scenarios indicate that the NO_2 concentrations will not exceed the threshold of the EU environmental quality standards.

Sensitivity analyses can also be used to evaluate different pathways towards a target. For example, to reach a specific future emission target, policy scenarios and "sensitivity" intervals in addition to the emission projection can provide key elements for improved communication and decision making. In this example (Figure 6), information on the underlying assumptions is needed to properly assess the robustness of the policy scenario.

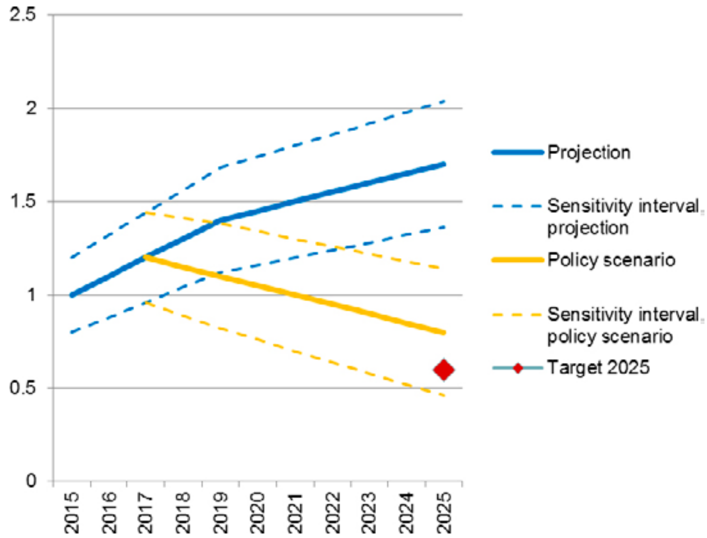

Figure 6. Schematic picture of emission target, projection and policy scenario, and sensitivity intervals. In this case, neither the projection nor the policy scenario reaches the target, but the target is inside the sensitivity intervals of the policy scenario.

Emission projection and scenarios play an important role in developing international, national and regional policies and measures to reduce emissions of greenhouse gases and air pollutants to the atmosphere. Implementation of the recommendations presented in this work would strengthen the basis in future air pollution work.

This work was presented at the SCAC conference in February 2017.

List of deliverables

D 2.1	An analysis and compilation of requirements and needs for projections from stakeholders for different purposes, levels of detail and on different geographical scales, including necessary background information *Kindbom, K., Gustafsson, T. (2015). Emissionsprognoser och scenarier – Behovsanalys. SCAC arbetspaket 2:1. IVL C121.*
D 2.2	Sensitivity analysis and ex-post analysis of Swedish projections identifying and quantifying important input parameters impacting projections results. *Included in D2:3*
D 2:3	A methodology for, and role of, sensitivity analysis of projections in a future Swedish system for projections. *Kindbom, K., Gustafsson, T. (2017). Känslighetsanalys som verktyg i arbetet med utsläppsprognoser. SCAC arbetspaket 2:2. IVL CXXX. In prep.*
D 2.4	A conceptual approach for future systematic and consistent development of Swedish emission projections and scenarios *Gustafsson, T., Kindbom, K. (2017). Så ska framtidens utsläppsprognoser tas fram. SCAC arbetspaket 2:3. IVL CXXX. In prep.*

WP 2.4 Knowledge gaps GAINS scenarios

The objective of this activity was to improve the robustness of Swedish air pollution emission projections and estimations of emission abatement potentials in particular for shipping, agriculture and industries (including EU-ETS).

The following research questions were addressed:

- Can time trend data on industrial energy use and economic value added provide robust estimates for emission projections from industrial activities?
- Will emission abatement in the North Sea and/or Baltic Sea regions provide a more cost-effective option to reduce environmental impacts in Sweden than national land-based emission reductions in 2020?
- How can alternative projections on agricultural activities affect key environmental aspects such as the Swedish nitrogen budgets and emissions of NH3 and CH4?

Background to the SCAC work with IAM

Within 2:4 we focused on developing GAINS Scandinavia model analysis of international shipping and on reviewing GAINS model NH_3 scenarios and corresponding Swedish NH_3 scenario. Within SCAC WP2 the GAINS Scandinavia model was extended with data on emissions, abatement options, and emission abatement costs for international shipping in the Baltic and the North Sea. This data is used within WP1 as basis for the WP1 Phase III cost optimization routine described above. The review of NH_3 scenarios focused on analysing differences between scenarios developed with the GAINS model for the European Commission and the corresponding Swedish scenarios developed by SMED. The report presents results from the discrepancy analysis, analysis of differences in which abatement options that are considered for the future, as well as a short analysis of the potential co-benefits and trade-offs between NH_3 and CH_4 emission abatement from the agricultural sector in Sweden. The efforts to improve analysis of emission abatement potential in industries were replaced with increased efforts on analysing emission abatement from international shipping. The part of WP 2.4 focusing on reporting uncertainties and discrepancies (D 2.5, linked to WP 1.1) led to the research application presented in D 1.1.

The GAINS model is an influential decision support model in today's European air pollution policy development. It is however not an entirely complete model, and in WP2 we have strived to complement the existing data in the model with scenario data on emissions and emission abatement from international shipping, a source of emissions that have not been controlled as much in the past as emissions from land-based sources. There are ongoing policy initiatives to reduce emissions from international shipping in the Baltic and North Seas (HELCOM 2016), but the decision support material needs to be improved and through the SCAC programme there is a potential to adjust the GAINS model to allow for analysis of emission abatement from shipping.

One of the sectors of increasing importance for European air quality is the agricultural sector. Recent analysis show that at least two high attention events of poor air quality in large European cities have been largely due to emissions of ammonia (Vieno et al. 2016, Petit et al. 2017). Emissions of ammonia are now considered to be the most important source of PM2.5 levels in Europe (Bauer et al. 2016). Despite this, European ambition levels for ammonia emission reductions is lower than the ambition level for other air pollutants, with a 19% emission reduction target by 2030 from 2005. For SO_2, NOx, VOC, and PM2.5 the corresponding numbers are 79%, 63%, 40%, and 49% (Airclim 2016). Consequently, there is a continued high demand to explore feasible options and opportunities for implementing control of European ammonia emissions.

Method

To analyse emissions, emission control costs, and emission control benefits for the shipping sector we used cost-benefit analysis (CBA) (Pearce et al. 2006, Boardman et al. 2010) and the impact pathway approach (Bickel and Friedrich 2005) applied to the questions of whether a nitrogen emission control area (NECA) would provide net socio-economic benefits for Europe. Within SCAC we gathered data on emission control costs and used these in combination with the GAINS model and existing tools for calculating monetary benefits of emission reductions (Alpha Risk-Poll).

For NH_3, we started the work with developing representation of ammonia emissions in the GAINS model through a survey of similarities and differences between the Swedish methods used to calculate current and future ammonia emissions with the method used in the GAINS model. The comparison was made with basis in the most recent emission inventories and scenarios. Furthermore, the comparison also included which emission control options are assumed to be implemented or available for further emission reductions.

Results achieved so far

Our analysis of the net socio-economic benefits of reducing emissions from international shipping shows that for most of the settings of the analysis, the benefits will exceed costs of introducing a NECA in the North Sea and in both the Baltic Sea and the North Sea in combination. For the Baltic Sea, the results are more mixed.

The comparison of Swedish and GAINS model ammonia calculations shows a continued need for review of differences. It also highlights the need for continued focus on the potential synergies and trade-offs between ammonia control and control of other pollutants and greenhouse gases. It is also important to more clearly identify existing knowledge gaps and develop a strategy for how to fill these gaps.

Implications for air quality work

The relatively clear socio-economic benefits of introducing a NECA in the Baltic and North seas gives good support for ensuring that the IMO efforts to introduce stricter emission control in the sea regions. Currently within SCAC we are re-evaluating these results and are comparing costs and effects of reducing emissions from land with costs and effects of reducing emissions from international shipping.

The results from our review of ammonia emissions shows continued need for strengthening the knowledge base supporting future negotiations on reducing ammonia emissions, which historically haven't been reduced to the same extent as other pollutants.

Deliverables

D 2.6	Manuscript *The Costs and Benefits of a Nitrogen Emission Control Area in the Baltic and North Seas* to be submitted.
D 2.6	IVL report *Ammonia emissions in Sweden – Inventories, projections and potential for reduction*, final draft finished A.S.A.P.

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Achievements WP 3: Health effects of particles in ambient air pollution

Aims

The aims of WP 3 were to a) develop and validate methods for estimating levels of respirable particulate matter (PM), such as PM_{10}, $PM_{2.5}$ and black carbon (BC) from different sources with appropriate time and spatial resolution to be used in epidemiological studies and health impact assessments; b) develop exposure-response functions for long-term exposure to respirable particulates from different sources with respect to morbidity and identify suitable health indicators; and c) make health impact assessments and damage cost estimates focusing on case studies including scenarios for reducing exposures.

Background

Health effects of air pollution are a key driver for future control of air pollution. A report on global burden of disease points to the importance of air pollution as a health hazard globally (Lim et al. 2012). Policy development has so far been mainly based on epidemiological studies on mortality but more recently there has been an increasing interest in other endpoints. Long-term exposure to air pollution has been associated with an increased risk of cardiovascular disease, partly by inducing systemic inflammation (Brook et al. 2010). The inhalable fraction of ambient particulate is considered to be responsible for most of the adverse health effects. However, the evidence is not conclusive on which particulate characteristics or sources are responsible for the effects. Available studies mainly implicate $PM_{2.5}$, and to some extent BC, but data on coarse particles are limited (WHO, 2013). Studies have not detected substantial deviations from linearity or provided evidence of thresholds.

Adverse health effects of ambient air pollution are prominent in children (Gruzieva 2012). For example, in a series of publications based on the BAMSE birth cohort from Stockholm exposure to air pollution from road traffic during the first year of life has been related to asthma, allergic sensitization and lung function disturbances up to 12 years of age. When SCAC was initiated there were no studies on effects by air pollution exposure during infancy in relation to development of asthma, allergy or lung function with follow-up until adolescence or adulthood.

Some studies indicate that exposure to air pollution negatively affects pregnancy outcome, such as the risk of low birth weight and prematurity (Slama et al. 2009, Olsson et al. 2012, Olsson et al. 2013). Since one of the major components of the foetal programming hypothesis is growth disturbance, as indicated by a low birth weight, this raises concerns that negative effects by air pollution in utero may also be of importance for adverse health effects later in life.

Assessments of health effects are strongly dependent on tools for linking exposure to sources and control measures. Models need to have appropriate time and space resolution (Gidhagen et al. 2013). Accurate estimation of concentrations of relevant air pollutants is essential for assessment of exposure-response relationships, and generally requires retrospective exposure data to study health effects of long-term exposure.

Health Impact Assessment (HIA) is used as a method to describe impacts of the current situation, future scenarios and policy options (Johansson et al. 2009, Orru et al. 2009). HIA is used at global, European (Andersson et al. 2009, Orru et al. 2013), national (Forsberg et al. 2005) and local levels (Omstedt et al. 2011) and can be included in broader cost-benefit analyses. A limitation is the uncertainties in the exposure-response functions for the effect of PM, and the lack of generally accepted exposure-response functions for many important morbidity endpoints.

Currently the main-stream economic valuation of health impacts caused by air pollution is limited. Certain health impacts are not yet monetized. Also, some non-lethal health impacts such as cardiovascular disease are most often valued according to the cost of incidence, e.g. cost of cardiac hospital admissions (Holland et al. 2011). The results from economic valuation were influential in setting the proposed ambition level of the new Clean Air Policy Package in the European Union. Holland (2014) has shown that despite the limited number of adverse health impacts included, the currently monetized morbidity impacts of air pollution constitutes up to 31% of total benefits from the proposed CAPP when the chosen economic value of mortality is low. If additional human health end points would be included in a future economic valuation, the resulting cost-efficient strategy for air pollution policy should imply benefits of larger efforts to reduce emissions.

Methods and results

The activities within WP 3 have been organized based on the three deliverables:

- 3:1 Exposure modelling
- 3:2 Estimation of exposure-response functions
- 3:3 Heath impact assessment and damage costs

3:1 Exposure modelling

High-resolution dispersion modelling was made for the period 1990 to 2011 and over three urban domains: Göteborg (93×112 km^2), Stockholm (174×236 km^2) and Umeå (109×182 km^2) (Figure 7). The analysis separately assessed the most important source categories of particle emissions in urban areas: road traffic (separately for exhaust and non-exhaust emissions), residential wood combustion, shipping and other activities (mainly industrial, large energy heat and power production plants, off-road machinery and agriculture).

Separate inventories were compiled for 1990, 2000 and 2011 (for Stockholm also for 1995 and 2005). For all three regions, there are local or regional bottom-up inventories available. For Umeå and Göteborg, the inventories were supplemented for consistency over the whole domain and time period (not necessary for Stockholm).

Small scale residential heating emissions were gridded with a resolution of 100×100 m^2 for the Stockholm and Göteborg areas. The energy consumption for the sector was based on energy balances provided by Statistics Sweden (SCB) and distributed spatially using proxy data such as number of appliances (stoves, boilers) per municipality, living space of small houses per km^2, population density per 100 m^2 and availability of district heating. For the Umeå area, a register of individual wood stoves and boilers was available, allowing these sources to be included as point sources. Fuel consumption was based on a household survey (Omstedt et al., 2014). For areas with availability to central heating it was assumed that fuel consumption was reduced by two thirds on average. Emission factors for PM_{10} and $PM_{2.5}$ are based on Omstedt et al. (2014) and the fraction of $PM_{2.5}$ corresponding to BC is taken from EMEP/EEA Inventory Guidebook 2013. There are large differences in emission factors depending on technology and age of stoves and boilers as well as firing habits. Due to lack of information regarding age and details of technology, the emission factors were aggregated according to Table 1. The limited knowledge of the technology used and firing habits contribute to significant uncertainties in the description of emissions from this sector, especially in Göteborg and Stockholm, where we do not have a complete inventory of individual stoves and boilers.

Table 1. Emission factors [mg MJ-1] applied for small scale residential heating.

Technology (fuel)	PM	BC
Stove	400	40
Boiler (oil)	7	0.6
Boiler (pellets)	28	7.8
Boiler (wood logs)	600	96

Road traffic emission factors for PM-exhaust for different vehicle types, speeds and driving conditions were calculated based on HBEFA 3.1 (Hausberger et al. 2009) and BC emission factors are based on the TRANSPHORM project (TRANSPHORM 2013), but corrected based on local measurements at a street canyon site in Stockholm (Krecl et al. 2017). Non-exhaust includes road wear and some contributions from brake and tire wear and emission factors were obtained from Omstedt et al. (2005).

Large industrial sources and energy production facilities were included in the model as point sources. For Göteborg and Umeå the main source of information was the yearly emission inventory compiled by SMED. For Stockholm the emission data is mainly based on annual environmental reports, obtained from supervisory authorities.

Emissions from shipping were described using a bottom-up approach including actual ship movements of all ships equipped with AIS (Automatic Identification System) transponders and ship properties acquired from international databases. The calculations are similar to those described by Jalkanen et al. (2012). Since only yearly average concentrations were of interest, the annual average distribution of emissions was used in the modelling and introduced as grids with a resolution of 1×1 km^2.

For Göteborg and Umeå, emissions from off-road machinery and diffuse emissions related to e.g. agriculture were also taken from SMED. In Stockholm, these emissions were disregarded in the exposure calculations due to a large uncertainty in absolute emissions and lack of information on the geographic location of the off-road machinery emissions. The contribution to the annual mean exposure of the population (and members of the cohorts) is likely to be small.

Gaussian models included in the Airviro air quality management system (SMHI, 2010) have been used to simulate annual average PM_{10}, $PM_{2.5}$ and BC levels. For Stockholm, a meteorological climatology (15 years, 60 wind direction sectors with 6 stability classes in each sector) was used as input to calculations 1990, 1995, 2000, 2005 and 2011, while for Göteborg and Umeå the simulations were performed with hourly meteorological data for 1990, 2000 and 2011. The two methods of simulating hour by hour or using a climatology were compared and found to have a high correlation (r=0.99). For the years in between, simulated concentrations were interpolated. To resolve concentration gradients in the vicinity of roads and point sources, a locally refined receptor grid was used. The receptor grids had an original coarse resolution ranging from up to 3×3 km^2 in rural areas without any emission sources and successively down to a minimum of around 35×35 m^2 along major roads and close to stacks.

The long-range annual average contributions from sources outside the modelling domains were determined either indirectly as the difference between total measured concentrations at one measurement station inside the modelling domain and the simulated local contribution at the same location, or taken from a measured or regionally simulated concentrations at a rural background monitoring station outside the modelling domain. Especially for Göteborg and Umeå, the monitoring data is scarce and for some years, trends had to be extrapolated using relations to other monitoring stations.

Hourly ozone and road traffic exhaust particle concentrations were calculated for 2003–2013 for the birth outcome study in Greater Stockholm. A new empirical methodology was developed and validated to calculate the ozone concentrations. This method is based on Gaussian modelling of NO_x concentrations and a relation between ozone and NO_x based on simultaneous measurements of ozone and NO_x in central Stockholm and at a rural location. The hourly concentrations of ozone and PM-exhaust were averaged to trimester concentrations at the home address of every individual family in the study. Details on this methodology and comparison with measurements are presented in Olsson et al. (2017).

Validation of PM_{10}, $PM_{2.5}$ and BC concentrations has been performed using available monitoring data not previously used for estimating contribution from long-range transport (LRT). The modelled concentrations were compared with measurements and the overall r^2 for all data from the three cities were 0.87 and 0.65 for PM_{10} and $PM_{2.5}$, respectively (Figure 8). The overall agreement is regarded as good considering the uncertainties in both the emission inventories and the dispersion models involved in these calculations.

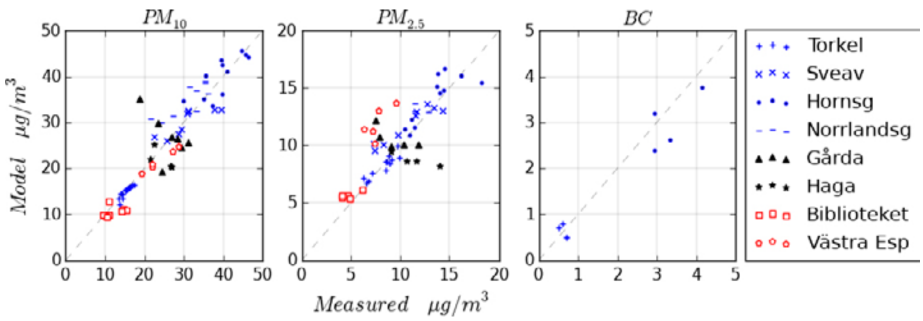

Figure 8. Comparison between modelled and measured concentrations of particulate matter. The colours represent the three cities, blue: Stockholm, black: Göteborg and red: Umeå.

The result of the exposure calculations is presented as population weighted annual mean concentrations for 35×35 km^2 squares centred over the three cities (Figure 9). The total impact of local sources of PM_{10}, $PM_{2.5}$ and BC concentrations are reduced from 1990 to 2011, but not the specific contributions of traffic wear and residential wood combustion (Figure 10). The year-to-year variation in total exposure concentrations seen in Figure 11, is mostly caused by variations in the contribution from LRT. The changes over time in the relation between PM_{10} and $PM_{2.5}$ in Göteborg raise some questions. It is possible that part of the contribution attributed to long-range transport can be explained by local sources, such as large construction works, that are not described in the emission inventories. There are also uncertainties in measurement data, especially during early years, which directly influence the estimation of the long-range transport. For total $PM_{2.5}$ there is a clear decreasing trend. BC concentrations show a dominance of local source contributions. Local $PM_{2.5}$ contributions are lower than the LRT, but show a somewhat increasing trend from 1990 to 2011 at all three locations.

It is noteworthy that for $PM_{2.5}$, exposure caused by small scale residential heating is comparable to exposure due to road traffic. For BC, exposure to traffic exhaust is larger than exposure caused by combustion emissions from residential heating. The large differences in emission factors for stoves and boilers of different technology and age imply a strong potential to reduce the emissions using low emission technology and cleaner fuels like pellets.

Results from Deliverable 3.1 have been summarized in manuscripts by Segersson et al. submitted to Journal of Exposure Science and Environmental Epidemiology (see reference list) and by Olsson et al. (2017).

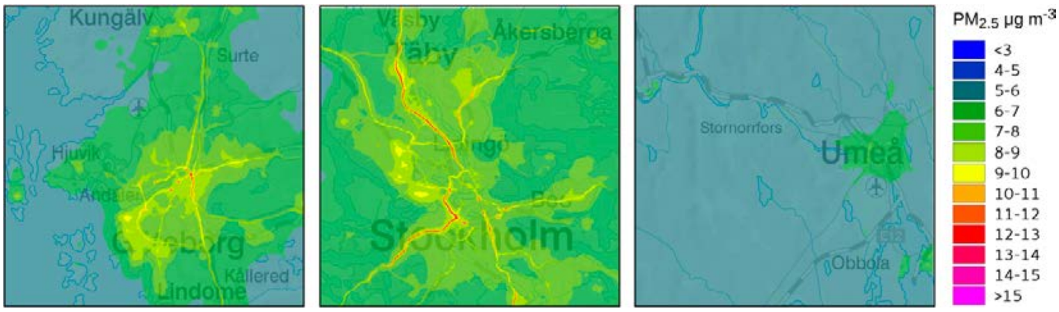

Figure 9. Annual average of total $PM_{2.5}$ concentration during 2011 presented in 35×35 km² areas centred on the main city of each modelling domain. ©Lantmäteriet.

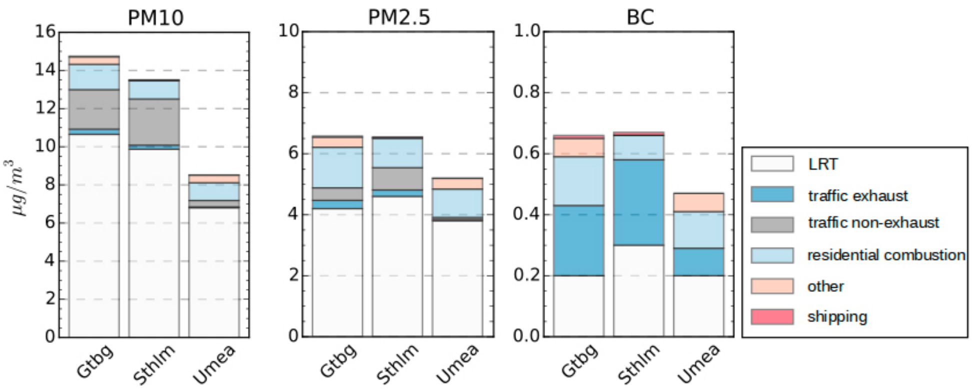

Figure 10. Sectorial contributions to PM10, PM2.5 and BC exposure during year 2011 in the three 35×35 km² areas with population data from 2012.

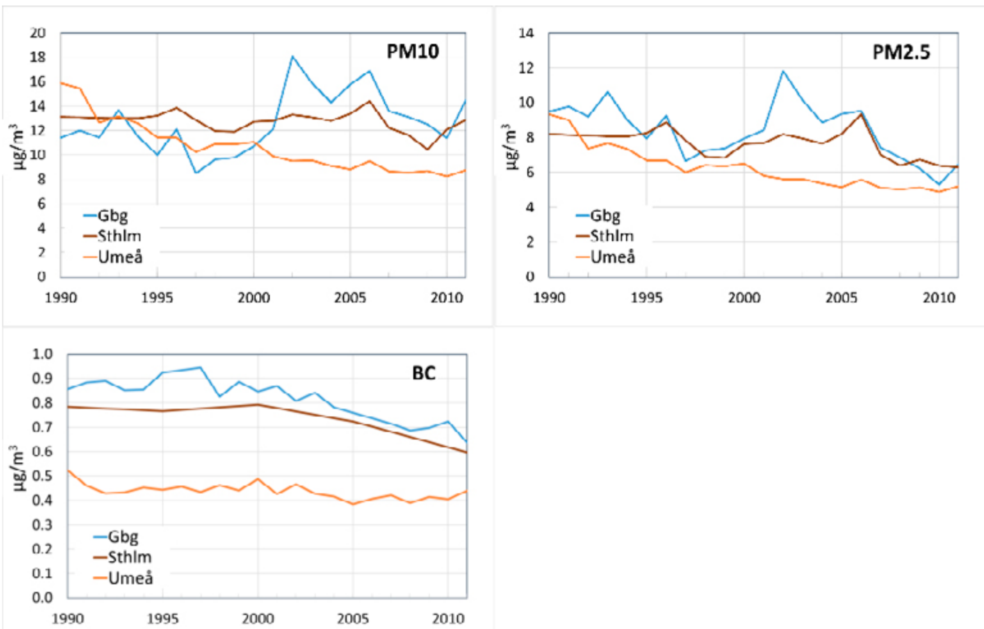

Figure 11. Calculated annual average exposure to PM_{10}, $PM_{2.5}$ and BC during 1990 – 2011 for the individual subjects in the cohorts inside the Göteborg, Stockholm and Umeå modelling domains.

3.2 Estimation of exposure-response functions

Using the exposure data from 3.1, exposure-response functions were calculated for PM_{10}, $PM_{2.5}$ and BC based on several epidemiological studies in the Göteborg, Stockholm and Umeå regions. The health endpoints include cardiovascular disease (ischemic heart disease and stroke), lung function effects in children, adolescents and adults as well as pregnancy outcomes, primarily low birth weight and prematurity.

Meta-analyses on *cardiovascular endpoints* were performed based on two cohorts in Göteborg, four cohorts in Stockholm and one large cohort in Umeå, totalling more than 100 000 study subjects. These cohorts contributed with 6 179 cases of ischemic heart disease (IHD) and 3 577 of stroke during the observation period. There were no clear trends in risk for these two cardiovascular diseases in relation to exposure to most of the particle components under investigation. However, a statistically significant increase in the hazard ratio was observed for stroke of 1.14 per µg (95 % confidence interval 1.01 to 1.28) in relation to exposure to BC during the year of the outcome assessment. For IHD there was an indication of heterogeneity between the cohorts with lower risks in relation to exposure observed in Umeå than in the two other areas. Analyses based on source specific particle components did not reveal any clear patterns. Our risk estimates appear compatible with results of earlier epidemiologic studies also using high resolution data on individual air pollution exposure, such as the European multicenter study ESCAPE. (www.escapeproject.eu).

Cross-sectional analyses in a cohort of close to 7 000 adults from Göteborg showed small but statistically significant reductions in *lung function* (FEV_1 and FVC[2]) related to exposure to all three types of particles from road traffic. For BC lung function deficits were seen also in relation to exposure to all particle sources taken together. In similar studies of a birth cohort from Stockholm including more than 4 000 children no statistically significant associations were seen at 16 years of age in relation to estimated exposure to PM_{10}, $PM_{2.5}$ or BC during different time windows from birth to the time of the lung function tests, although suggested deficits in lung function occurred for all time periods and particle types. In earlier studies using a similar exposure assessment methodology, but focusing on emissions related to road traffic only, reductions in lung function were observed at both 8 and 16 years of age related to exposure during the first year of life (Schultz et al. 2012, Schultz et al. 2016). This study used PM_{10} as a marker of exposure to coarse particles related to road traffic, mainly road dust, while NOx was used as a marker of exhaust emissions, also including particles. For example, the FEV_1 associated with a 5 µg increment in PM_{10} exposure during the first year of life was –41.0 ml (95 % CI –78.1 to –3.9) and –34.3 ml (95 % CI –86.6 to 17.9), respectively, at 8 and 16 years of age.

[2] FEV_1: Volume that has been exhaled at the end of the first second of forced expiration.
FVC: The vital capacity from a maximally forced expiratory effort.

For the *birth outcome* study all singleton births in the Greater Stockholm area that were conceived between August 2003 and February 2013 were included, n = 251 559. The studied outcomes were preterm birth (PTB), *i.e.* being born before 37 weeks of gestation, and small for gestational age (SGA), defined as having a birth weight below the 10^{th} percentile for the given duration of gestation stratified by sex. Exhaust particle exposure was associated with SGA throughout pregnancy, the odds ratio (OR) per 200 ng/m^3 increase during the first trimester was 1.09 (95 % CI 1.06 to 1.11) and similar for the second trimester and for the whole pregnancy. There was a tendency of a positive association between first trimester ozone exposure and PTB, the OR per 20 µg/m^3 increase was 1.05 (95 % CI 0.99 to 1.10). An additional meta-analysis with our new results for the period 2007–2013 (OR = 1.06) and two earlier studies covering the period from 1987–1995 and 1998–2006, yielded an OR of 1.10 (95 % CI 1.04 to 1.16) (Olsson et al. 2012; Olsson et al. 2013).

Results from Deliverable 3.2 are included in manuscripts by Carlsen at al., Ljungman et al., Olsson et al. and Stockfelt et al. intended for international publication (see reference list).

3.3 Health impact assessment and damage costs

The calculated particle exposure levels in 3.1 are used to estimate the burden of disease in terms of mortality, and as incidence of stroke and myocardial infarction attributed to the studied air pollutants. The simulated exposure is presented as population weighted concentrations for 35×35 km^2 squares centred over the three study areas Göteborg, Stockholm and Umeå.

Exposure was calculated on a 100×100 m^2 grid acquired from Statistics Sweden, representing the year 2012. Data were based on the coordinates for the home addresses of the total population. Baseline mortality rates representing all natural deaths in the age group 30+ in the three counties were acquired from the Swedish Cause of Death Register at The National Board of Health and Welfare. To avoid double counting, only one particle fraction was used to represent the impact of each source category in the health assessment. For particles originating from local sources, three different exposure-relations coefficients are used to demonstrate the range of the risk estimates; a) Jerrett et al (2005), who investigated associations within a metropolitan area (Los Angeles), b) Hoek et al (2013) with a compilation of several studies and finally c) Janssen et al (2011) providing an estimate for BC (actually representing a mixture of BC, EC and BS (black smoke). These literature-based exposure-response functions were considered more stable and established than those derived from the SCAC cohorts.

Preterm mortality is calculated separately for the main local sources and long-range transport (LRT). In general, the main part of the exposure is due to LRT, while for black carbon, the local sources are equally or more important.

Although LRT dominates the exposure, the majority of the premature deaths are attributed to local emissions, with road traffic and residential wood combustion having the largest impact if ER-functions from Jerrett et al

(2005) or Janssen et al (2011) are assumed most relevant for local sources of combustion particles. For Stockholm, the percentage of the premature deaths caused by local sources that are related to "traffic < 2.5µm" is estimated to 66% when using BC as an indicator and around 40 % using $PM_{2.5}$. In Umeå RWC represents 40–60% of the premature deaths due to local sources. For Göteborg and Stockholm, RWC is somewhat less important and represents 20–50 % of the premature deaths related to local sources.

The calculated particle exposure levels in 3.1 are also used to estimate the burden of disease in terms incidence of stroke and myocardial infarction among person aged 30+. Initially this assessment is built on European estimates from the large ESCAPE study, also including Swedish cohorts. The relative risks applied are from the meta-analysis of effects on the incidence of stroke (Staffogia et al. 2014) and on acute coronary events (Cesaroni et al. 2014), respectively. For stroke the overall relative risk was 1.33 (95% CI 1.01, 1.77) per 5 µg/m^3 and for myocardial infarction 1.23 (1.04, 1.46) per 5 µg/m^3. In this case there are no source specific relative risks to apply. Baseline incidence rates for the three counties were collected from The National Board of Health and Welfare for the year 2011. For stroke this resulted in estimated 773 (95% CI 750, 1031), 400 (95% CI 12, 9349 and 48 (95% CI 1, 112) extra cases per year for Stockholm, Göteborg and Umeå, respectively. For myocardial infarction the estimates were 621 (95% CI 108, 1242), 360 (95% CI 12, 720 and 47 (95% CI 8, 86) for Stockholm, Göteborg and Umeå, respectively. In total, about half of the estimated cardiovascular disease burden was associated with the local contribution of $PM_{2.5}$.

The birth outcome study has also been used to estimate the impacts of air pollution. The fraction of preterm births attributable to ambient ozone levels was calculated based on a meta-analysis of risk estimates from two earlier studies of trimester specific ozone levels (mean of daily 8h max) and preterm delivery from the Greater Stockholm (Olsson et al. 2012, Olsson et al. 2013) area along with the new results from SCAC, which provided a meta estimate, OR=1.049 (95% CI 1.021 to 1.078) per 10 µg/m^3. This OR has been used to calculate an attributable fraction in Greater Stockholm during the period 2004–2013. This estimate is close to the estimate from the two largest recent studies (Laurent el al. 2016, Lavigne et al. 2016). The proportion of cases attributable to a higher ozone level was calculated as the number of cases among exposed divided by the total number of cases. To scale this to a national level the proportion of cases attributable to ozone was multiplied with a factor representing the ratio between the national population weighted modelled annual (2012) mean of daily ozone maximum 8h level and the corresponding modelled mean for Stockholm at Torkel Knutssonsgatan in Stockholm. Finally, the national total number of cases attributable to a higher ozone level was calculated by multiplying the national number of cases with the national proportion of cases attributable to a higher ozone level. The estimated proportion of cases of preterm birth in Sweden attributable to ozone is 1.9 % (95% CI 0.8 to 2.9), or 126 per year (estimated from 2010 data).

A corresponding calculation was done for children born with a low birth weight in relation to gestational length (Small for Gestational Age, SGA) and the concentration of local PM exhaust, using the observed OR 1.11 (95% CI 1.08 to 1.15) per 200 ng/m^3 for the whole pregnancy. The estimated proportion of SGA cases attributable to exhaust particles in Greater Stockholm is 1.7% (95% CI 1.3 to 2.1). To scale this to a national level the proportion of cases attributable to PM exhaust was multiplied with a factor representing the ratio between the national population weighted modelled annual mean (2010) and the corresponding modelled mean for the population of Greater Stockholm in a national assessment (Gustafsson et al. 2014). The proportion of children born as SGA attributable to PM exhaust in Sweden was estimated to 0.9% (95% CI 0.6 to 1.1), or 97 per year (estimated from 2010 data).

The damage costs associated with preterm birth were valued using the method proposed by Hodek et al. (2011). The data needed for estimation of unit economic values was taken from national statistics on level of education, income, and life expectancy (Statistics Sweden 2016, The public health agency of Sweden 2016); and national statistics on health care costs (SKL 2016). Data on incidence rates for long term impacts specified per gestational group were taken from Lindström et al. (2007). The quality-of-life impacts were assumed to be life-long. The damage costs associated with SGA were not estimated due to limited data on long term health impacts and the estimation of damage costs associated with stroke and myocardial infarction were not estimated due to limited cost data. The Swedish damage costs associated with PTB caused by exposure to air pollution in 2010 are valued to 2–25 million €.

Results from Deliverable 3.3 are summarized in manuscripts by Segersson et al. and Åström et al. intended for international publication (see reference list).

Conclusions

- For exposure of PM_{10} and $PM_{2.5}$ the long-range contribution is larger than the impact of local sources, while for black carbon the local impact is equal or larger.
- Road traffic and small-scale residential heating emissions are the largest local sources of particle and black carbon exposure. Road wear particles are the dominant local source of PM_{10}, small-scale residential heating dominates for $PM_{2.5}$ and traffic exhaust is the largest local source of black carbon.
- The exposure modelling in SCAC has been crucial for estimation of exposure-response functions and for health impact assessments related to air pollution. It is useful also for similar applications in the future.
- There was an increased risk of stroke related to recent exposure to BC but no associations were seen for other types of particles and cardiovascular outcomes.

- Exposure to particles appeared to reduce the lung function in adults and similar effects were suggested in adolescents. Earlier studies showed that exposure to traffic-related air pollution during the first year of life negatively affected lung function at 4, 8, and 16 years of life.
- There was an association between exposure to exhaust particles during the initial part of pregnancy and low birth weight.
- Observed exposure-response relations for the different health effects investigated in SCAC appear compatible with results from other studies.
- Although long range transport is the major source of $PM_{2.5}$, the majority of the premature deaths are attributed to local combustion particles when source specific exposure-response functions are applied.
- Residential wood combustion seems to be more important for exposure to fine particles and related health impacts than usually assumed.
- We have initiated work with expanding the types of health impacts included in economic valuation of air pollution. The full inclusion of state of the art knowledge about morbidity impacts of air pollution in economic valuation will influence the total economic valuation of air pollution and have an impact on which policy ambition level that is cost-efficient.

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Achievements WP 4: Climate and ecosystem effects

Outline of the research activities

The research was organised in four activities:

- 4:1 SLCP distribution and radiative forcing
- 4:2 Evaluation of climate metrics for SLCP
- 4:3 Forest ozone exposure and effects on carbon sequestration
- 4:4 Review of critical load calculations

Background and state of the art

SCLP (4.1 and 4.2). The two acronyms SLCF – Short-lived Climate Forcers, and SLCP – Short-lived Climate Pollutants have been introduced in recent years to represent chemical components that influence the earth's radiation balance and have relatively short residence time in the atmosphere – a few days to a few decades (Quinn et al., 2008; Ramanathan and Xu, 2010). The focus has primarily been on agents that exert a warming effect (mainly BC and ozone), but short-lived components include also cooling agents, e.g. aerosol particles containing scattering material such as sulphate or organic matter. The influence on climate by aerosols depends on the chemical composition, size distribution and mixing state of the aerosol as well as the underlying surface. Adding to the complexity, aerosol particles may affect the optical and microphysical properties of clouds, by acting as cloud condensation nuclei and by modifying the thermodynamic structure of the atmosphere. These indirect effects of aerosol particles on clouds generally cool the climate but the effect, just as the direct one (i.e. the scattering or absorption of solar radiation), is highly uncertain (IPCC, 2013). Several studies show that the indirect effects are very hard to observe, as for example shown in a recent study of the aerosol effects on low-level clouds over the Nordic Countries that combined in-situ ground-based aerosol measurements with remote sensing data of clouds and precipitation(Sporre et al, 2014).

Translating aerosol RF into an actual surface temperature change is also not straight-forward; areas subjected to a positive aerosol forcing may not necessarily experience a surface temperature increase and vice versa (Shindell and Faluvegi, 2009; Lewinschal et al., 2013). The climate at mid- and high-latitude areas are also influenced by aerosol emission trends in the tropics as heat fluxes transfer some of the influence of forcings between tropics and extra-tropics.

UNEP/WMO (2011) estimated that broad implementation of 16 existing emission reduction measures targeting BC and tropospheric ozone would reduce global warming by 0.5°C in 2050 and would improve the chance of not exceeding the 2°C target, but only if long-lived GHG such as CO_2 were simultaneously addressed. More recent work in the FP7-project ECLIPSE and in AMAP indicate that the potential is substantially lower, 0.22±0.07 K (Stohl et al., 2015).

The uncertainties in net climate forcing from BC-rich sources are substantial; largely due to lack of knowledge about cloud interactions with both black carbon and co-emitted organic carbon (Bond et al., 2013). Simulated global burdens of BC differ by more than a factor of two between models and the calculated average residence time range from 4.9 to 11.4 days (Schulz et al. 2006). Differences in burdens of BC over the Arctic exceed a factor of five. It is therefore important to try to further constrain and improve model simulations of aerosol compounds including BC.

Ozone and carbon sequestration (4.3). Ozone represents an important threat to forest growth in the Northern Hemisphere and the impacts of current ozone levels on the growth are well established (Wittig et al., 2009) as are the impacts on Swedish forests (Karlsson et al., 2009). A first estimate showed that current ozone levels may reduce forest carbon sequestration in some northern and central European countries in the order of 10 % (Karlsson, 2012). A remaining uncertainty, however, is the quantification of the ozone impacts on the growth of mature forests under field conditions.

The current target values set for ozone impacts on human health and vegetation impacts within the national environmental objective “Clean Air” are exceeded by far (Swedish EPA, 2012 rapport 6500). In future control strategies the aspects of ecosystems and health effects need to be considered together with the effects on climate.

Review of Critical Loads (4.4). The methodology to calculate critical loads (Nilsson and Grennfelt, eds. 1988) has evolved over time depending on the availability of detailed regional data and increased process understanding. At the same time, the gap between actual deposition and critical loads has decreased which has led to increased requirements for accuracy and reliability in the concepts and models used. The methodology has also developed with regards to the criteria for critical load calculation and multiple connections to chemistry-biology. Ecosystem effects examined include toxicity to fish and benthos, the ratio between base cations and aluminium in the soil water linked to toxicity to roots and also changes in the species composition of the ground vegetation layer. A dynamic concept (target loads, Jenkins et al., 2003) was developed to complement the critical load for acidification.

Activities 4:1 and 4:2: SLCP distribution and radiative forcing and evaluation of climate metrics for SLCP

Part of the work in activity 4.1 and 4.2 was aligned with the assessment work carried out in the Arctic Monitoring and Assessment Program (AMAP) expert group on black carbon and ozone as climate forcers. The work has been documented in several journal publications and in the AMAP assessment published in 2015 (AMAP, 2015). An example of results from a model-data intercomparison of the seasonal variation of BC in the Arctic is shown in Figure 12. The models NorESM and MATCH that were used in SCAC are both included. Comparisons of radiative forcing estimates between Earth System Model (ESM) and Chemical Transport Model (CTM) simulations are documented in AMAP (2015) and underpinned the conclusions on climate effects of SLCPs in that report. Work on applying the offline coupled model system MATCH-SALSA-RCA4 (Thomas et al., 2015) where a high resolution CTM with detailed aerosol dynamics is coupled to a regional climate model over the northern hemisphere was continued. Work on comparing observed and model simulated cloud cover was completed within the SCAC project.

D4.1	Report documenting evaluation of ESM and CTM model simulations of SLCPs for current climate and emissions using available observations. Eckhardt et al. (2015); Emmons et al. (2015); Arnold et al. (2015); Monks et al. (2015); Mahmood et al. (2016); AMAP (2015) – chapter 8.
D4.2	Manuscript documenting and comparing RF estimates for SLCP from ESM and CTM simulations. AMAP (2015) – chapter 11.

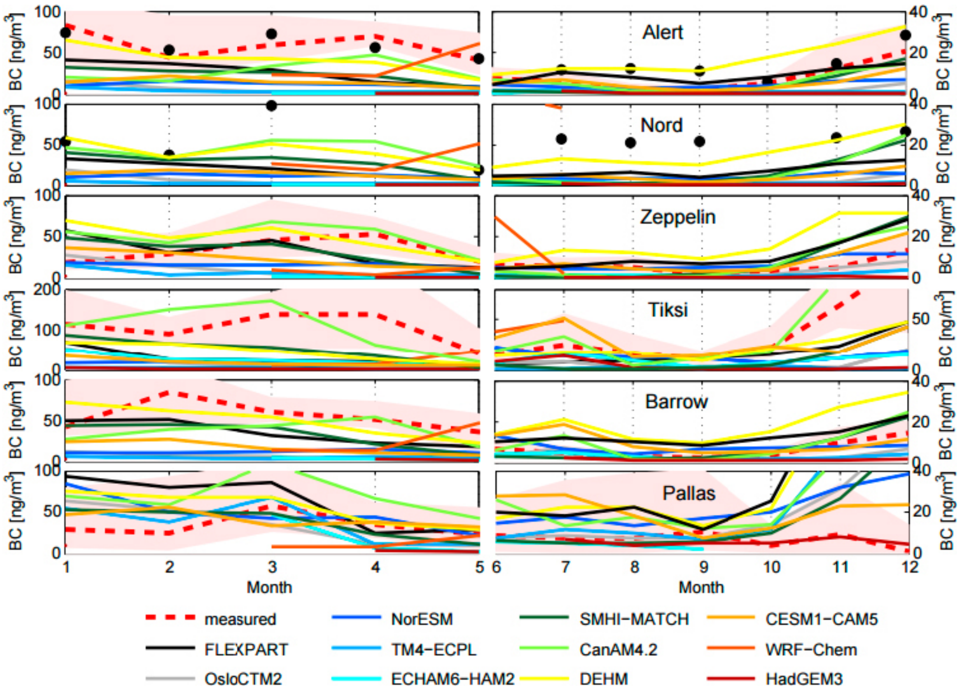

Figure 12. Surface concentrations of monthly median observed BC or EC and modeled BC for the years 2008–2010. Eckhardt et al. (2015).

The work within WP4 has clearly shown that aerosol emission changes in one region, e.g. Europe, affect climate in other regions, such as the Arctic. As sulphate aerosol emissions over Europe have decreased since the 1980's, the Arctic has warmed by 0.5 K, both due to changes in transport of aerosol particles to the Arctic region (and a subsequent local direct and indirect forcing) and to changes in heat transport from lower latitudes. Currently, the proportion between local (changes in aerosol particle transport and loading over the Arctic) and remote warming (changes in heat transport) is not clear and needs further research. Within the EU-PEGASOS framework, WP4 has also conducted simulations for the future and estimated the relative impact of changes in aerosol particle emissions and greenhouse gases. The simulations show that by 2050, a reduction of global aerosol emissions from fossil fuels following a maximum technically feasible reduction scenario could lead to a global and Arctic warming of 0.3 K and 0.8 K, respectively; as compared with a simulation with fixed aerosol emissions at the level of 2005. After 2050, changes in greenhouse gas emissions dominate the anthropogenic temperature change, if the greenhouse emissions follow the IPCC RCP4.5 scenario.

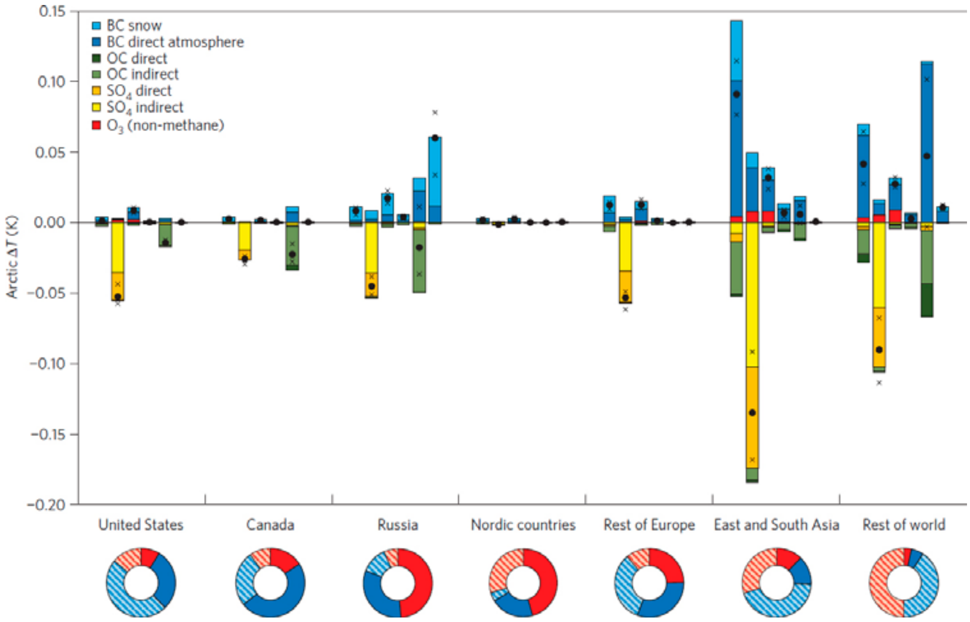

Figure 13. Arctic equilibrium surface temperature response. Each bar represents emission sectors for each source in order from left to right: domestic, energy/industry/waste, transport, agricultural waste burning, grass/forest fires, and flaring. The doughnuts illustrate how much of the Arctic warming (red) and cooling (blue) comes from forcing within the Arctic (solid fill) versus outside the Arctic (striped). Sand et al. (2016).

WP4 has also contributed to the work in AMAP (2015) where the contribution from different emission sectors and pollutants to Arctic temperature change was further disentangled based on the concept of regional temperature potentials, RTP. This is a concept which relates temperature change in a specific region, e.g. the Arctic, to radiative forcing from different pollutants in different latitude bands on the globe. The RTP coefficients were based on simulations with a global climate model (Shindell and Faluvegi, 2009). Figure 13, taken from Sand et al. (2016), shows the different SLCP contributions to current Arctic temperature changed based on the RTP concept.

D4.3	Report on climate effects of SLCP emissions from ESM simulations. Sand et al. (2016); Acosta Navarro et al. (2016); Acosta Navarro et al. (2017)

One goal of WP4 has been to analyse the robustness and usefulness of different relations (metrics) such as the RTP concept for climate impacts in Integrated Assessment Models (IAMs). Fully coupled (ocean-atmosphere+chemistry) simulations have been conducted with NorESM to obtain RTP coefficients relating aerosol emissions (sulphate, black carbon, organic carbon) in different regions (Europe, North America, South Asia and East Asia) to temperature change in other regions (collaborative effort with CICERO, Norway). The actual temperature response in NorESM has been compared with that derived using effective radiative forcing (ERF) estimates from the same model in combination with RTP values found in the literature (ERF+RTP response). Effective radiative forcing includes the effects of rapid adjustments of atmospheric temperatures, clouds and moisture (IPCC, 2013). Figure 14 shows an example of such a comparison. In general, the ERF+RTP estimated temperature change for a certain SO_2 emission change agrees well with the temperature response obtained in NorESM. However, one region where the ERF+RTP estimated value does not agree so well is the Arctic, which is problematic from a policy perspective.

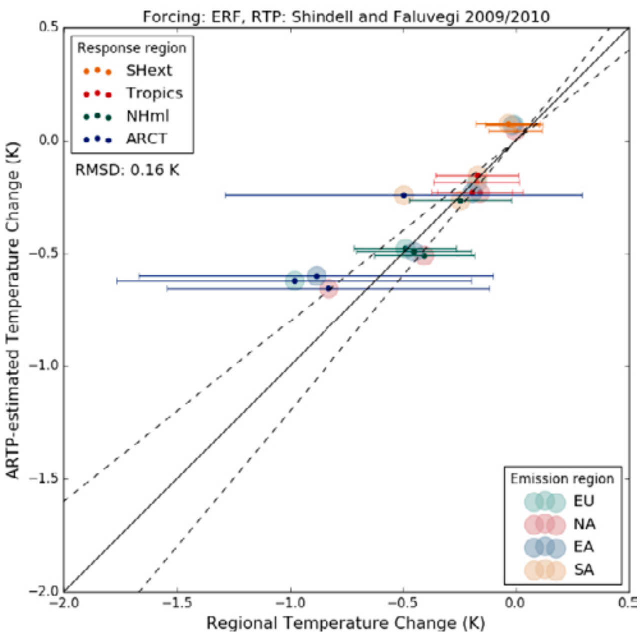

Figure 14. Temperature response derived from ERF and non-normalised RTPs (vertical axis) vs. simulated temperature response (horizontal axis) in NorESM. Colors of large dots indicate the emission perturbation region and color of small dots indicate the latitude band of the temperature response. The horizontal bars indicate one standard deviation for the temperature response in NorESM. The dashed lines show ±20% agreement thresholds.

D4.4	Report on results of comparison and analysis of climate effects accounted for in GAINS with effects simulated in both the ESM and CTM simulations for the same emission scenario. (Lewinschal et al., *in prep).*

Activity 4:3 Forest ozone exposure and effects on carbon sequestration

A European network was established with the aim to agree on scientifically sound methods to assess epidemiological analysis of air pollution effects on vegetation. The first Expert Workshop on Epidemiological Analysis of Air Pollution Effects on Vegetation was held in Basel (Switzerland) from 16–17 September 2014. The workshop was attended by experts from Italy, Sweden, Switzerland and the United Kingdom. The second Expert Workshop on Epidemiological Analysis of Air Pollution Effects on Vegetation, was organized by IVL Swedish Environmental Research Institute and Gothenburg University, and was held in Hindås outside Gothenburg, Sweden, 23–24 November 2015. That workshop was co-funded by SCAC and the strategic research programme BECC and was attended by 24 scientists from Finland, Italy, Sweden, Spain, Switzerland, and United Kingdom. The workshops resulted in a set of methodology recommendations for epidemiological Analysis of Air Pollution Effects on Vegetation, published as a report on the website of ICP Vegetation (http://icpvegetation.ceh.ac.uk/) as well as a scientific paper (Braun et al., accepted for publication in Science of the Total Environment, Feb 2017, see deliverables).

A study was completed on the trends for future ozone concentration dynamics and ozone indices for health and ecosystems that was initiated already in the CLEO programme and presented in Karlsson et al. (2017). The main conclusions from the study were that the highest ozone concentrations are decreasing while low and medium high ozone concentrations are increasing. Hence, future ozone impacts on health and ecosystems will depend more on chronic exposure to medium rather than high peak concentrations.

A database was established with annual tree stem basal area increment growth over the time period 1990–2013 as the dependent variable and ozone exposure, nitrogen deposition, air temperature, precipitation and several more meteorological variables as well as forest stand characteristics as explanatory variables. Annual stem growth was estimated for Norway spruce, Scots pine and European beech at altogether 25 different forest observation sites distributed over the southern part of Sweden using tree ring analysis. Ozone exposure was estimated as AOT40/30 based on modelled hourly ozone data from the MATCH model. Nitrogen wet deposition was estimated from monitoring data from the Swedish Throughfall Monitoring network as well as from "Luft- och Nederbördskemiska nätet". Meteorological parameters were provided by SMHI. Stand characteristics were available from the Swedish Forests Agency observation plots. The database was completed in Sept 2016 for all Norway spruces sites (18 sites) and statistical analyses were initiated. Preliminary results indicated a negative impact of ozone on the annual stem growth and a positive effect of nitrogen deposition.

The abatement of the ozone pollution problem clearly has the co-benefit to increase the carbon sequestration in northern and central European forests for at least some decades into the future. A frame-work methodology was suggested for how to include ozone impacts on forest carbon sequestration in the GAINS model, as the delivery D 4.5 to WP 1. The methodology is illustrated in Figure 15. The main uncertainty in this type of assessments will be the quantification of ozone impacts on mature trees under stand conditions. There are several ongoing studies addressing this uncertainty, one of which is under way in the SCAC program.

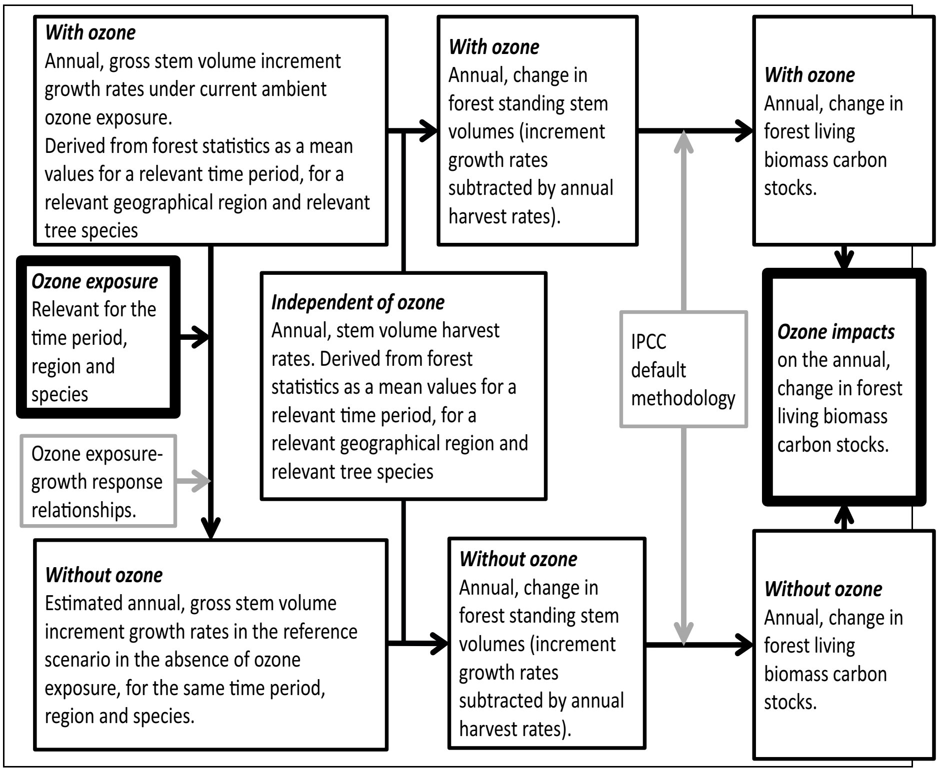

Figure 15. Illustration of a frame-work methodology for how to include ozone exposure impacts on forest carbon sequestration in the GAINS model.

Deliverables

D 4.5	Report on suggestions for improvements of the descriptions of ozone impacts on forest carbon sequestration in GAINS. Per Erik Karlsson, Håkan Pleijel & Hans Linderholm. Deliverable for WP 1, 2016-02-23.
D 4.6	Scientific article on ozone exposure of forest in Sweden over the last 20 years: Karlsson et al. (2017) Scientific article on methodology for epidemiological analysis of ozone impacts on ecosystems: Braun et al. Accepted for publication in Science of the Total Environment, Feb 2017.

Activity 4:4 Review of critical load calculations

Shifting focus from damage to ecosystem health to protecting biodiversity, and accounting for the influence of other factors such as land use change and climate change are the main factors influencing the development of critical loads calculations methodology. An expert workshop was organised to summarize current status of methodology and metrics to calculate critical loads for acidification and for eutrophication, with efforts partly devoted also to critical loads for heavy metals. The workshop took place in conjunction with meeting of Joint Expert Group on Dynamic Modelling under the CLRTAP Working Group on Effects (WGE) at 29–31 October 2014 in Sitges, Spain. Twenty two expert experts from 11 countries participated in the workshop and the results were summarized in report submitted to the Working Group on Effects under the CLRTAP. The report presents a summary of the progress in dynamic modelling of ecosystems effects by acidification, heavy metals and nutrient nitrogen including the interactions between climate change and air pollution, biological responses and terrestrial carbon sequestration. Outcomes of the expert meeting were also presented at first joint session of WGE and EMEP in Geneva in September 2015.

D4.7	Discussion paper, workshop and workshop report on methodology to calculate critical loads. Report submitted to WGE. http://www.unece.org/fileadmin/DAM/env/documents/2015/AIR/EMEP/ECE_EB.AIR_GE.1_2015_19_ECE_EB.AIR_WG.1_2015_12_ENG.pdf

Conclusions WP 4

- Model simulations indicate that the Arctic has warmed by 0.5 K since 1980's due to sulphur emission reductions over Europe. This is about half of the observed warming in the Arctic since 1980. Further, by 2050, a reduction of global aerosol emissions from fossil fuels could lead to a global and Arctic warming of 0.3 K and 0.8 K respectively, compared to 2005.
- Impacts on Arctic temperatures are highest for emissions inside the Arctic. The impact on Arctic temperatures from emissions in Europe, North America and East Asia are higher per emitted amount than from South Asia.
- The contribution from different sectors and pollutants to Arctic temperature change has been studied using the RTP concept. Analyses of robustness of the concept show less agreement for the Arctic, an issue to be further investigated.
- Air pollution emission reductions in sectors with a high share of black carbon emissions such as diesel, gas flaring and others could lead to reduced warming although large uncertainties still remain.

- If COP21 targets on reductions of long-lived greenhouse gases are realized the importance of air pollution mitigation for climate change will increase.
- Assessments of ozone impacts on vegetation have to be adapted to fact that the highest ozone concentrations are decreasing while low and medium high ozone concentrations are increasing.
- In order to evaluate ozone effects on trees, a database on annual stem growth has been established for Norway spruce, Scots pine and European beech at 25 different forest observation sites in southern part of Sweden. Statistical analysis of the data is presently ongoing.
- The present understanding of dynamic effects to ecosystems from nitrogen deposition was evaluated through an international workshop.

Communication activities WP 4

Scientific papers

1. *Acosta Navarro, J. C. & Varma, V., Riipinen, I., Seland, Ø., Kirkevåg, A., Struthers, H., Iversen, T., Hansson, H.-C., Ekman, A. M. L. 2016. Amplification of Arctic warming by past air pollution reductions in Europe. Nature Geoscience, 9, 277–281, doi:10.1038/ngeo2673.
2. *Acosta Navarro, J. C., Ekman, A. M. L., Pausata, F., Lewinschal, A., Varma, V., Seland, Ø., Gauss, M., Iversen, T., Kirkevåg, A., Riipinen, I., Hansson, H.-C., 2017 Future response of temperature and precipitation to reduced aerosol emission as compared with increased greenhouse gas concentrations. *Journal of Climate*., 30, 939–954. DOI: 10.1175/JCLI-D-16-0466.1
3. *AMAP, 2015. AMAP Assessment 2015: Black carbon and ozone as Arctic climate forcers. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. vii + 116 pp.
4. *Arnold, S. R., Emmons, L. K., Monks, S. A., Law, K. S., Ridley, D. A., Turquety, S., Tilmes, S., Thomas, J. L., Bouarar, I., Flemming, J., Huijnen, V., Mao, J., Duncan, B. N., Steenrod, S., Yoshida, Y., Langner, J., and Long, Y. 2015. Biomass burning influence on high-latitude tropospheric ozone and reactive nitrogen in summer 2008: a multi-model analysis based on POLMIP simulations, Atmos. Chem. Phys., 15, 6047–6068, doi:10.5194/acp-15-6047-2015.
5. *Braun, S. Achermann, B., De Marco, A., Pleijel, H., Karlsson, P. E., Rihm, R., Schindler, C., Paoletti, E. Epidemiological analysis of ozone and nitrogen impacts on vegetation – critical evaluation and recommendations Accepted for publication in Science of the Total Environment, Feb 2017.

6. *Eckhardt, S., Quennehen, B., Olivié, D. J. L., Berntsen, T. K., Cherian, R., Christensen, J. H., Collins, W., Crepinsek, S., Daskalakis, N., Flanner, M., Herber, A., Heyes, C., Hodnebrog, Ø., Huang, L., Kanakidou, M., Klimont, Z., Langner, J., Law, K. S., Lund, M. T., Mahmood, R., Massling, A., Myriokefalitakis, S., Nielsen, I. E., Nøjgaard, J. K., Quaas, J., Quinn, P. K., Raut, J.-C., Rumbold, S. T., Schulz, M., Sharma, S., Skeie, R. B., Skov, H., Uttal, T., von Salzen, K., and Stohl, A. 2015. Current model capabilities for simulating black carbon and sulfate concentrations in the Arctic atmosphere: a multi-model evaluation using a comprehensive measurement data set, Atmos. Chem. Phys., 15, 9413–9433, doi:10.5194/acp-15-9413-2015.
7. *Emmons, L. K., Arnold, S. R., Monks, S. A., Huijnen, V., Tilmes, S., Law, K. S., Thomas, J. L., Raut, J.-C., Bouarar, I., Turquety, S., Long, Y., Duncan, B., Steenrod, S., Strode, S., Flemming, J., Mao, J., Langner, J., Thompson, A. M., Tarasick, D., Apel, E. C., Blake, D. R., Cohen, R. C., Dibb, J., Diskin, G. S., Fried, A., Hall, S. R., Huey, L. G., Weinheimer, A. J., Wisthaler, A., Mikoviny, T., Nowak, J., Peischl, J., Roberts, J. M., Ryerson, T., Warneke, C., and Helmig, D.: The POLARCAT Model Intercomparison Project (POLMIP) 2015. overview and evaluation with observations, Atmos. Chem. Phys., 15, 6721–6744, doi:10.5194/acp-15-6721-2015.
8. *Karlsson, P. E., Klingberg, J., Engardt, M., Andersson, C., Langner, J, Pihl Karlsson, G. and Pleijel, H. 2017. Past, present and future concentrations of ground-level ozone and potential impacts on ecosystems and human health in northern Europe. Science of The Total Environment 576, 22–35.
9. *Mahmood, R., K. von Salzen, M. Flanner, M. Sand, J. Langner, H. Wang, and L. Huang 2016. Seasonality of globaland Arctic black carbon processes in theArctic Monitoring and Assessment Programme models, J. Geophys. Res.Atmos., 121, 7100–7116, doi:10.1002/2016JD024849.
10. *Monks, S. A., Arnold, S. R., Emmons, L. K., Law, K. S., Turquety, S., Duncan, B. N., Flemming, J., Huijnen, V., Tilmes, S., Langner, J., Mao, J., Long, Y., Thomas, J. L., Steenrod, S. D., Raut, J. C., Wilson, C., Chipperfield, M. P., Diskin, G. S., Weinheimer, A., Schlager, H., and Ancellet, G. 2015. Multi-model study of chemical and physical controls on transport of anthropogenic and biomass burning pollution to the Arctic, Atmos. Chem. Phys., 15, 3575–3603, doi:10.5194/acp-15-3575-2015.
11. *Sand, M., Berntsen, T. K., von Salzen, K., Flanner, M.G., Langner, J, Victor, D.G. 2016. Response of Arctic temperature to changes in emissions of short-lived climate forcers, Nature Climate Change, 6, 286, doi: 10.1038/NCLIMATE2880

Conferences

1. Ekman, A. M. L., Acosta Navarro J.-C., Varma V., Riipinen I., Seland O., Kirkevåg A., Struthers H., Iversen T. & Hansson H.-C. The Climate Response of Regional Air Pollution Changes. Goldschmidt conference, Prague, 16–21 August, 2015. *INVITED SPEAKER*.
2. Ekman, A. M. L., Acosta Navarro J.-C., Varma V., Riipinen I., Seland O., Kirkevåg A., Struthers H., Iversen T. & Hansson H.-C. Arctic climate response to regional aerosol emission changes between 1980 and 2005. 2015 AGU Fall Meeting, San Francisco, 14–18 December, 2015. *INVITED SPEAKER*.
3. Lewinschall, A. Regional aerosol emissions and temperature response: Local and remote climate impacts of regional aerosol forcing, Aerocom meeting, Beijing, September 2016. Poster.
4. Thomas, M. Evaluation of prognostic aerosol-cloud interactions by combining a chemistry transport model with a regional climate model. Symposium on Coupled Chemistry-Meteorology/Climate Modelling, Geneva, Switzerland, 23–25 Feb 2015.
5. Thomas, M. Meteorological conditions associated with extreme pollution events over the Nordic countries. Air Quality conference, Milan, Italy, 14–18 March, 2016.
6. Thomas, M. An observational perspective of the impact of atmospheric weather states on carbon monoxide levels in the free troposphere over the Nordic countries. Air quality conference, Garmisch Partenkirchen, Germany, 24–28 March, 2014.

Seminars:

1. June, 2016: Invited to Leipzig University, Germany to present “Arctic climate response to regional aerosol emission changes”, Annica Ekman.
2. April, 2015, Stockholm, Nordic Seminar on the Arctic Climate – How to put SLCP policies into practice, “Introduction to Short-Lived Climate Pollutants”, Joakim Langner.
3. March, 2015 Stockholm: Seminar on Ground-level ozone – present-day and future risks for impacts on vegetation, “Ozone – an important short-lived greenhouse gas”, Joakim Langner.
4. April, 2014, Miljöpartiet Stockholms stadshus: ”Klimatpåverkande luftföroreningar SLCP”, Joakim Langner.

Media:

1. December, 2015: Interviewed by the Swedish Broadcasting Company TV4 regarding the topic “2015 can be the warmest year so far”.
2. March, 2016: Interviewed by Radio Sweden, Washington Post and Carbon Brief about our study on “European clean air policies unmask Arctic warming by greenhouse gases”.

3. April, 2016: Interviewed by Radio Sweden regarding "the life of a scientist".
4. May, 2016: Interviewed by Radio Sweden regarding the topic "can forest fires affect weather and climate?"
5. August, 2106: Interviewed by the Swedish Public Broadcasting Company SVT regarding the topic "increasing extreme weather in a warmer climate?"
6. December, 2016: Interviewed by the Swedish Public Broadcasting Company SVT regarding the climate in 2017.

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SCAC Communication

The scientific communication has mainly been through peer-reviewed journals and technical reports. Several publications and reports are completed or in the pipeline for submission or publication (see above and at http://www.scac.se/publications). Results are also reported at a large number of international and national conferences. This is an example shown for WP4.

Within SCAC, communication with the main stakeholders is an ongoing activity and many of the scientists are involved in policy-directed national and international expert groups. Among the most important, we want to mention the Air Convention (WGE and EMEP, ICP Vegetation, Task Force on Modelling and Mapping, Task Force on Hemispheric Air Pollution Task Force on Emissions Inventories and Projections etc.), WHO, CCAC, AMAP/Arctic Council and the European Union.

More specifically we will mention the following activities and actions:

- SCAC participation by Hans Christen Hansson, Stefan Åström, John Munthe and Peringe Grennfelt in the UNECE Assessment Report *Towards cleaner air*.
- Participation in and organisation of the 5th Saltsjöbaden workshop in 2013 https://www.saltsjobadenV.ivl.se
- The second Expert Workshop on Epidemiological Analysis of Air Pollution Effects on Vegetation on 23–24 November 2015, organized by IVL Swedish Environmental Research Institute and Gothenburg University and co-funded by SCAC. The workshop was attended by 24 scientists from Finland, Italy, Sweden, Spain, Switzerland, and United Kingdom.
- Seminar *How to put SLCP policies into practice* on 17th of April 2015 arranged by SCAC, SMHI, Nordic Council of Ministers and the Ministry of the Environment and Energy.
- Seminar *Ground-level ozone – present day and future risks for impacts on vegetation* on March 9th 2015.
- Participation by SCAC-researchers Joakim Langner (SMHI), HC Hansson (ITM), Karin Kindbom (IVL), Håkan Pleijel, (UGOT) and Christer Johansson (ITM and SLB) in a Swedish-Chinese workshop in Beijing in January 2014 regarding SLCPs.
- The main outcome of the program was presented and communicated at a final of SCAC Phase 1 conference in Gothenburg on February 7th 2017. The conferences also discussed results and coming actions needed within the field.
- At the conference a glossy summary of the main achievements of the first phase of SCAC was presented, which can be found at the programme's web page.

Program management

The program was directed by a management group, having teleconferences about every second month, at which each work package gave an update and the areas for coordination were discussed. In addition, the meetings also included an exchange of information with respect to the development of actual policies (from the policy side) and recent results that could be of interest for policies. Within each work package, meetings were also held regularly. Every year there were annual meetings, at which all activities were represented. At these meetings progress of each work package was presented and discussed. In large the time plan for the program was followed and those minor changes that were necessary did not influence the overall outcome and time plan for the program.

Representatives from the Swedish Environmental Protection Board working within the area of air pollution policies, both nationally and internationally, were invited to all meetings with the management board as well as to annual meetings. The participation of these experts and their willingness to give all involved in the programme insight in the policy needs and applications of our results were highly acknowledged by all participants within the programme.

Table 2 Management board

Name	Function
Peringe Grennfelt, IVL	Program coordination
John Munthe, IVL	Applicant, Deputy coordinator, coordination with relevant research activities at IVL
Lars Gidhagen, SMHI	Coordination with relevant air quality and research activities at SMHI
Karin Sjöberg, IVL	Coordination with relevant air quality activities at IVL
HC Hansson, SU	WP 1 co-lead
Stefan Åström, IVL	WP 1 co-lead
Karin Kindbom, IVL	WP 2 co-lead
David Segersson, SMHI	WP 2 co-lead
Göran Pershagen, KI	WP 3 co-lead
Gerd Sällsten, GU	WP 3 co-lead
Annica Ekman, SU	WP 4 co-lead
Joakim Langner, SMHI	WP 4 co-lead
Erik Swietlicki, LU	Coordination with research activities at LU

Research in support of Air Pollution Policies

Results from the first phase of the Swedish Clean Air and Climate Research programme

Final report

REPORT 6784

SWEDISH EPA
ISBN 978-91-620-6784-7
ISSN 0282-7298

The aim of the research program SCAC was to develop and improve the scientific basis for air pollution policies on national and international scales including relations to climate policy. The focus of the program was hemispherical transport of air pollution and action strategies in Europe.

FORSKNING FÖR MILJÖMÅLEN

NATURVÅRDSVERKETS FORSKNINGSANSLAG

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