Swedish Clean Air and Climate Research Programme – SCAC

Final report second phase

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scac
Swedish Clean Air and Climate Research Program
Frisk luft och Klimat

MILJÖ | NATURVÅRDSVERKET
FORSKNING

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final report second phase

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Förord

Rapporten för Swedish Clean Air and Climate Research Programme, SCAC-fas 2 presenterar forskningresultat som stödjer Naturvårdsverkets arbete med miljömålen Frisk luft samt Begränsad klimatpåverkan och svarar på ett stort behov av vetenskaplig kunskapsbas i nationella och internationella diskussioner och förhandlingar och utveckling av ny politik för luftföroreningar. Forskningen inriktar sig på hemisfärisk transport av luftföroreningar och åtgärdsstrategier i Europa.

Programmet har finansierats med medel från Naturvårdsverkets miljöforskningsanslag vilket syftar till att finansiera forskning till stöd för Naturvårdsverkets och Havs- och vattenmyndighetens kunskapsbehov.

Denna rapport är författad av forskningsprogrammets konsortium i vilket ingår IVL Svenska Miljöinstitutet, SMHI, Umeå Universitet, Karolinska Institutet, Göteborg Universitet, Göteborg Botaniska Trädgård, Chalmers, och International Institute for Applied Systems Analysis (IIASA).

Författarna ansvarar för rapportens innehåll.
Naturvårdsverket september 2020

Preface

The final report for the phase two of the Swedish Clean Air and Climate Research Program (SCAC) presents research results that support the Swedish Environmental Protection Agency's (Swedish EPA) work with the environmental quality goals of Fresh Air and Limited Climate Impact. The research responds to the need for scientific basis in national and international negotiations and to development of new science-based policies on air pollution. The research focuses on hemispheric transport of air pollutants and action strategies in Europe.

The research program has been funded by the Swedish EPA's environmental research grant, which aims to fund research in support of the Swedish EPA and the Swedish Marine and Water Authority's knowledge needs.

This report is written by the consortium of the research program which includes IVL Swedish Environmental Research Institute, SMHI, Umeå University, Karolinska Institute, University of Göteborg, Göteborg Botanical Garden, Chalmers, and International Institute for Applied Systems Analysis (IIASA).

The authors are responsible for the content.
Swedish EPA, September 2020

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1 Sammanfattning

Fas 2 av forskningsprogrammet SCAC startades för att fortsätta utveckla den vetenskaplig kunskapsbasen kring luftföroreningar som ligger till grund för nationellt åtgärdsarbete och internationella förhandlingar om utsläppsminskningar. Specifikt inriktades programmet på fyra huvudområden där kunskap behövdes för att stödja utveckling av ytterligare åtgärdsstrategier: interaktioner mellan luftföroreningar och klimat samt hemisfärisk transport; luftföroreningar och hälsa med fokus på partiklar från transport och vedeldning; ekosystemeffekter (och samverkan mellan luftföroreningar - klimatförändring) av ozon och kväve, det senare med tonvikt på nationella kvävebudgetar och biologisk mångfald. Slutligen ingick utveckling av integrerad bedömningsmodellering för identifiering av effektiva åtgärdsstrategier.

1.1 Samverkan luftföroreningar och klimat

Forskningen om samverkan mellan luftföroreningar och klimat i SCAC-2 har gett resultat som är relevanta för utveckling av kostnadseffektiva åtgärdsstrategier för luftföroreningar och klimat. Inriktningen har varit att utvärdera hur förändringar i utsläppen av svavel och partiklar i Europa och andra regioner på norra halvklotet har påverkat klimatet.

Modellering med en avancerad jordsystemmodell och med emissionsscenarier för svavel och sot har visat att minskade utsläpp av svavel vid medel-breddgrader orsakar ökade temperaturer och värmetransport i atmosfären och en ökad uppvärmning i Arktis. Minskade utsläpp av sot leder i stället till minskad värmetransport och en kylande effekt. När det gäller klimatpåverkan per massenhet leder utsläppsminskningar av sot (minskad uppvärmning) till en 3–5 gånger större temperaturförändring i Arktis jämfört med svavel (minskad kylning). Temperaturförändringen som en funktion av förändringen i partikelutsläpp är icke-linjär med större temperaturförändring vid lägre utsläppsnivåer.

Tillsammans med resultat från andra liknande studier har en grund för klimat-neutrala åtgärdsstrategier utvecklats inom ramen för LRTAP-konventionen och i EU. Resultaten kommer även att ingå i en kommande rapport från AMAP om klimatpåverkande luftföroreningar som syftar till att ta fram vetenskapliga bevis till stöd för ytterligare åtgärder i länderna inom Arktiska Rådet.

Modellberäkningar med en hemisfärisk kemi- och transportmodell med IIASAs senaste utsläppsscenarier för gällande lagstiftning (Current Legislation) visar att det årliga medelvärdet av PM2.5 i bakgrundsluft i södra Sverige kommer att minska med 10% till 2030 jämfört med 2020, och med 15% till 2040. Om ett scenario för ytterligare åtgärder (Maximum Feasible Reduction) modelleras blir minskningarna 35 och 40% för 2030 och 2040. Minskningarna beror i första hand på emissionsminskningar i Europa. För ozon kommer medelvärdet av det högsta dygnsvärdet för perioden april till september att minska med ca 6% till 2030 och till 9% till 2040, jämfört med 2020 och enligt scenariot med dagens lagstiftning. För scenariot med ytterligare åtgärder minskar halterna för samma tidsperioder med 20 och 30%. Ändringarna i ozonhalt påverkas i större utsträckning av hemisfärisk transport än för PM.

1.2 Hälsoeffekter av luftföroreningar

Resultaten från SCAC stöder de senaste rapporterna att när man använder partikelmått som bestäms av koncentrationerna som härrör från lokala källor som trafik, kommer den relativa riskökningen per ökad koncentration att vara högre än annars. Detta gäller till exempel förhållandet mellan avgaspartiklar och dödlighet och förhållandet mellan sot från avgaser och stroke. En större betydelse av lokala partikelkällor för ökad risk innebär att hälsoeffekter uppstår på nivåer inte bara under miljökvalitetsnormerna för PM10 och PM2.5 utan även under de svenska preciseringarna av miljökvalitetsmålen. Den nya kunskapen om exponerings-responsförhållanden visar att beräkningar av hälsoeffekter baserade på äldre antaganden signifikant underskattar potentiella hälsofördelar med minskad exponering för lokala källor som stadsbiltrafik.

Hög korrelation mellan flera typer av föroreningar, inklusive avgaspartiklar, kvävedioxid och vägdamm, komplicerar tolkningen av resultaten i studier från en enda miljö och motiverar vidare forskning där effekten av olika föroreningar studeras i flera olika miljöer med olika korrelationer mellan nivåer.

En specifik fråga inom SCAC gällde hur effektiviteten av olika åtgärder för att minska partiklarnas hälsokonsekvenser beror på vilka mått på exponerings- och exponeringsrespons som använts i hälsokonsekvensberäkningar. Flera förhållanden motiverar utvärdering av hälsoeffekter av partikelexponering i Sverige, trots att vi har låga nivåer av föroreningar i en internationell jämförelse. Studier under senare år indikerar att skillnader i exponering vid låga nivåer inte bara är betydelsefulla ur hälsosynpunkt utan också kan ge större relativa förändringar i risk per koncentrationsförändring än vid högre koncentrationer. Partikelfraktionernas sammansättning skiljer sig också mellan länder.

SCAC har inkluderat studier av sambandet mellan exponering för olika typer av partiklar och risken för specifika hälsoeffekter, och litteraturöversikter med fokus på partiklar från vägslitage och vedeldning, problem som är av större relativ betydelse i Sverige än i många andra länder. Hälsokonsekvensbedömningar har också utförts för att belysa hur avgörande för slutsatserna det är att använda relevanta antaganden om exponeringssvar för olika typer av partiklar. Eftersom hälsoeffekterna av luftföroreningar domineras starkt av dödsfall, oavsett om hälsokostnader eller förlust av funktionellt vägda liv beräknas, är känslighet i beräkningarna av dödsfallseffekter central. Vidare styrks betydelsen och motiveringen av att tillämpa höga koefficienter som återspeglar den ”innerstadsvariationen” som nyligen rapporterats för

ACS av flera nya studier. Dödlighetsanalyserna som sammanställts för SCAC-kohorterna ger också höga koefficienter i förhållande till lokala trafikrelaterade partiklar, vilket tyder på att det är olämpligt att använda WHO: s rekommendation när man bedömer inverkan av lokala trafikrelaterade partiklar på dödligheten. Under 2019 reviderade Trafikverket därför sin modell (ASEK) för effekter och hälsokostnader.

1.3 Ozon

Forskningen inom SCAC har fokuserat på att bedöma geografiska och tidsmässiga trender för ozonkoncentrationer i förhållande till klimataspekter och risker för skador på vegetationen. Resultaten har rapporterats som bidrag till LRTAP-konventionen, särskilt till ICP-Vegetation och Task Force on Measurements and Modeling (TFMM).

När det gäller klimatfaktorer resulterade den varma och torra sommaren 2018 i högre ozonnivåer i södra Sverige jämfört med vad som annars hade varit fallet, allt annat konstant. Ett varmare klimat orsakar en tidigare start av växtsäsongen, om än med starka årliga variationer. En utvärdering av kunskapsläget visade att risken för signifikant och bestående negativ inverkan på vegetationen i nordliga ekosystem är begränsad och i alla fall inte större än i södra Fennoscandia. I genomsnitt har ozonkoncentrationerna i Sverige minskat under sommaren, men halterna på våren har ökat och ökningen sker tidigare på året i nordliga delar av landet. Detta utvecklingsmönster beror på 1 / minskande utsläpp av ozonbildande ämnen i Sverige och Europa, 2 / ökade utsläpp i Asien som påverkar interkontinental transport och 3 / ett förändrat klimat. Det sista resulterar i ett ökat ozonupptag till vegetation i maj månad, vilket kan resultera i en större negativ påverkan på grund av den tidigare början av växtsäsongen. Sammantaget har förändringarna lett till ett minskat överlapp mellan vårens högsta ozonhalter och växtsäsongen i Sverige, men det är fortfarande en fråga om den faktiska påverkan på vegetationen under våren har förändrats över tiden.

Mätningar och utvärdering av stamtillväxtdata från granskogar i södra Sverige tillsammans med miljö- och klimatdata visar att stamtillväxt är signifikant förknippad med antalet dagar med torka under växtsäsongen, medan det finns en indikation på positiv koppling till högt kvävenedfall och temperatur. Studien visade ingen koppling mellan stamtillväxt och ozonexponering eller växtsäsongens början och det drogs slutsatsen att en betydligt större datamängd skulle krävas för att detektera effekterna av ozon och kväve på trädtillväxt i Sverige med statistisk signifikans.

1.4 Kväve

SCAC-forskning om kväve har utförts inom ramen för flera aktiviteter inom LRTAP-konventionen: utveckling av nationella kvävebudgetar (NNB), TFMM, Task Force on Reactive Nitrogen (TFRN) och Joint Expert Group on Dynamic Modeling.

SCAC har bidragit till en svensk NNB genom att kartlägga de atmosfäriska mängderna. Svenska utsläpp av reaktivt kväve (Nr), nedfallsdata samt bidrag från import och export genom långväga transporter sammanställdes för 2015. Kvävet som deponerats över Sverige (160 tusen ton, kt) 2015 härstammar främst från andra länder (139 kt) medan tre fjärdedelar av de svenska kväveutsläppen (49 kt av de totala utsläppen på 70 kt) transporterades till andra länder. Den årliga Nr-omsättningen i atmosfären ovanför Sverige är cirka 210 k Nr, med tillskott (import + svenska utsläpp) på 209 kt och bortförsel på 213 kt (total deposition + export). Budgeten är balanserad inom 1% vilket även bör ses som ett mått på osäkerhetsmarginalen för de enskilda budgetposterna.

I SCAC har potentiella effekter av kvävenedfall på ekosystem utvärderats genom analys av information från tidigare experiment med kvävegödsel i svenska skogsekosystem. Det begränsade antalet experiment har gjort det svårt att dra slutsatser om långsiktiga effekter på biologisk mångfald. Gödslingsförsöket i Gårdsjön tyder på hög stabilitet i sammansättningen av vegetationsarter med relativt blygsamma och långsamma förändringar på en tidsskala av årtionden.

1.5 Hur välja rätt åtgärder för att säkerställa fördelar mellan klimat- och luftföroreningar?

Strategier för att minska utsläppen av luftföroreningar och växthusgaser tas fram som en del av internationella avtal, vanligtvis baserade på resultat från integrerade bedömningsmodeller (IAM). I SCAC har forskningen bidragit till den fortsatta utvecklingen av en sådan modell (GAINS-modellen) och dess rutin för optimering av åtgärdskostnader så att den nu, i en skandinavisk version, kan identifiera kostnadsminimerande sätt att minska effekterna på människors hälsa, miljö och klimat från utsläpp av SLCF beaktande osäkerheter i åtgärdskostnadsdata.

SCAC-forskning har också möjliggjort en gemensam analys av kostnadseffektivitet av utsläppsminskningar till sjöss och till lands och att utvärdera effekterna på koldioxidutsläpp vid implementering av teknik för emissionsminskning av luftföroreningar. Vidare har SCAC-forskning bidragit till beskrivning av skadekostnader för tre hälsoeffekter kopplade till dålig luftkvalitet

En specifik studie har visat att användningen av olika klimatmätvärden som indikatorer på klimatförändringseffekter från utsläpp till atmosfären inte påverkar resultaten när det gäller vilka åtgärder som modellen prioriterar för att minska utsläppen. Så den förvirring som orsakas av alla de olika klimatmätvärdena som finns i litteraturen är av mindre betydelse för arbetet med prioritering av åtgärder för att kontrollera luftföroreningar och klimateffekter.

SCAC-resultat visar också att effektivitetsförbättringar, användning av energikällor utan förbränning och beteendeförändringar alla bidrar till fördelar för både klimat och luftföroreningar, även om vissa risker för avvägningar kan identifieras. Först och främst kan användningen av fasta biobränslen för el och uppvärmning minska koldioxidutsläppen men riskerar att öka utsläppen av vissa luftföroreningar. För det andra riskerar användningen av flexibla mekanismer som EU:s system för handel med utsläppsrätter att geografiskt placera utsläppsminskningar i områden där fördelarna med luftkvaliteten är lägre än vad som kunde ha uppnåtts om man även beaktar effekterna på luftkvaliteten. Beteendeförändringar, även små och stegvisa, har både betydande effekter på utsläpp av luftföroreningar och innebär samfördelar mellan klimatförändringar och luftföroreningar.

2 Summary

The SCAC-2 program was initiated to provide an extended scientific knowledge base in national and international discussions and negotiations on the development of new air pollution policies and measures. Specifically, the program was focused on four main areas where additional knowledge was needed to support further actions: air pollution and climate interactions and hemispheric transport; air pollution and human health with focus on particles from transport and domestic wood burning; ecosystem effects (and air pollution – climate interactions) of ozone and nitrogen, the latter with emphasis on national nitrogen budgets and biodiversity. Finally, integrated assessment modelling and identification of the most efficient abatement strategies was included.

2.1 Air pollution and climate interactions

SCAC 2 research on air pollution and climate interactions has yielded results relevant for the development of cost effective and co-beneficial mitigation strategies for air pollution and climate change with focus on how changes in sulphur and particulate emissions in Europe and other major emission regions in the northern hemisphere affect climate.

Modelling using an advanced Earth System Model and emission scenarios for sulphur and back carbon has shown that reduced emissions of sulphur at mid-latitudes cause increased temperatures and heat transport in the atmosphere and an increased warming of the Arctic. Reduced emissions of black carbon lead instead to reduced heat transport and a cooling effect. In terms of *climate impact per unit mass*, emission reductions of soot (reduced warming) result in a 3-5 times larger Arctic temperature change compared to sulphur (reduced cooling). The temperature change as a function of the change in particle or precursor emissions is non-linear with a greater temperature change at lower emission levels.

Along with similar studies with other climate models, a scientific basis for climate neutral air pollution measures is created within the framework of the LRTAP Convention and the EU. Similarly, the results will be included in the forthcoming AMAP report on SLCF and climate, which aims to provide scientific evidence for continued action in the countries of the Arctic Council.

Model calculations using a hemispheric chemistry transport model show that the annual average level of $PM_{2.5}$ in background air in southern Sweden may decrease by about 10% in 2030 and about 15% in 2040 compared to 2020 based on IIASA's latest "current legislation" (CLE) emission scenario. The corresponding numbers for the "maximum feasible reduction" (SDS_MFR) scenario are 35 and 40% respectively. These changes are primarily due to emission reductions in Europe. For ozone, the level of the April-September mean of the daily maximum ground-level ozone in background air in Sweden may decrease by about 6% in 2030 and about 9% in 2040 compared to 2020 based on IIASA's latest CLE emission scenario. The corresponding numbers for the SDS_MFR scenario are 20 and 30% respectively. For these changes hemispheric transport is more important than for PM.

2.2 Human health impacts from air pollution

The results from SCAC support recent reports that when using particle matrices that are determined by the concentrations resulting from local sources such as traffic, the relative risk increase per increased concentration will be higher than otherwise. This applies, for example, to the relation of exhaust particles with mortality and to the relationship between soot from exhaust gases and stroke. The importance of local particle sources for the increase in risk means that health effects occur at levels not only below the environmental quality standards for PM_{10} and $PM_{2.5}$, but even under the Swedish specifications of the environmental quality targets. The new knowledge on exposure-response relationships shows that health impact calculations based on older assumptions significantly underestimate potential health benefits with reduced exposure to local sources such as urban car traffic.

High correlation between several types of pollutants, including exhaust particles, nitrogen dioxide and road dust, complicates the interpretation of the results in studies from a single environment and motivates further research where the effect of different pollutants is studied in several different environments with different correlations between levels.

One specific issue within SCAC concerned how the effectiveness of various measures to reduce the health consequences of the particles depends on the measures of exposure and exposure response functions adopted in health consequence calculations. Several conditions justify the investigation of particle health effects in Sweden, despite the fact that we have low levels of pollution in an international comparison. Studies in recent years indicate that differences in exposure at low levels are not only significant from a health point of view but may also give greater relative changes in risk per concentration change than at higher concentrations. The composition of the particle fractions also differs between countries.

SCAC has included studies of the relationship between exposure to different types of particles and the risk of specific health effects, and literature reviews focusing on road wear dust and wood smoke, problems that are of greater relative importance in Sweden than in many other countries. Health impact assessments have also been performed to elucidate how crucial for the conclusions it is to use relevant exposure-response assumptions for different types of particles. Since the health impacts of air pollution are strongly dominated by deaths, regardless of whether health costs or loss of disability adjusted life years are calculated, sensitivity in the calculations of mortality effects is central. Furthermore, the significance and rationale of applying high coefficients reflecting the "inner city variation" recently reported for ACS is substantiated by several recent studies. The mortality analyses compiled for the SCAC cohorts also give high coefficients in relation to local traffic-related particles, which indicates that it is inappropriate to use the WHO recommendation when assessing the impact of local traffic-related particles on mortality. In 2019 The Swedish Transport Administration accordingly revised their model (ASEK) for impacts and health costs.

2.3 Ozone

SCAC research has focused on assessing geographical and temporal trends of ozone concentrations in relation to climate aspects and risks for damage on vegetation. The results have been reported and provided as input to the LRTAP Convention, in particular to the ICP-Vegetation and the Task Force on Measurements and Modelling (TFMM).

In terms of climate factors, the hot and dry summer in 2018, resulted in higher ozone levels in southern Sweden compared to what would otherwise have been the case, all else constant. A warmer climate causes an earlier start of the thermal growing season, albeit with strong interannual variations. An evaluation of the state of knowledge indicated that the risk of significant and lasting negative impact on the vegetation in northern ecosystems is limited and, in any case, not greater than in southern Fennoscandia. On average, ozone concentrations in Sweden have decreased in summer, but springtime concentrations have risen and occur earlier in the year in northern parts of the country. This pattern of development is due to 1/ decreasing precursor emissions in Sweden and Europe, 2/ increased Asian emissions impacting though inter-continental transport, and 3/ a changed climate. The last includes increasing ozone uptake to vegetation in May, which could result in larger impacts, due to the earlier start of the growing season. In total, this has led to a *decreased* overlap between spring peak ozone and the growing season in Sweden, but it remains a question whether the actual springtime impact on vegetation has changed over time.

Measurements and evaluation of stem growth data from spruce forests in southern Sweden together with environmental and climate data show that stem growth is significantly negatively associated with the number of days of drought during the growing season, while there is an indication of positive association with high nitrogen deposition and temperature. The study showed no association of stem growth with ozone exposure or growing season onset and it was concluded that a substantially larger data set would be required in order to detect the effects of ozone and nitrogen on tree growth in Sweden with statistical significance.

2.4 Nitrogen

SCAC research on nitrogen has been performed within the framework of the several activities under the LRTAP Convention: the development of national nitrogen budgets (NNB), TFMM, the Task Force on Reactive Nitrogen (TFRN) and the Joint Expert Group on Dynamic Modeling.

SCAC has contributed to a Swedish NNB by mapping of the Atmosphere pool. Swedish emissions of reactive nitrogen (Nr), deposition data, contributions from import and export through long-range transport were compiled for 2015. The nitrogen deposited over Sweden (160 thousand tonnes, kt) in 2015 originated mainly from other countries (139 kt), while three quarters of the Swedish nitrogen emissions (49 kt of the total emissions of 70 kt) were transported to other countries. The annual Nr turnover in the atmosphere above Sweden is about 210 k Nr, with inputs (import + Swedish emissions) of 209 kt and output of 213 kt (total deposition + export). The fact that the budget is balanced within 1% should be seen as well within the margin of uncertainty for the individual budget items.

In SCAC, potential effects of nitrogen deposition have been assessed by analysis of information from earlier nitrogen fertilization experiments in Swedish forest ecosystems. The limited number of experiments have made it difficult to draw conclusions on long-term impacts on biodiversity. The fertilization experiment in Gårdsjön indicate high stability in the composition of vegetation species with relatively modest and slow changes at decadal time scale.

2.5 How to choose the right measures to ensure co-benefits between climate and air pollution solutions?

Strategies to reduce emissions of air pollution and greenhouse gases are within international agreements usually based on results from integrated assessment models (IAM). In SCAC, research has contributed to the continued development of the GAINS model control cost optimization routine so that it now, in a Scandinavian setting, can find cost-minimizing ways to reduce effects on human health, environment and climate from emissions of SLCFs and allow for consideration of uncertainty in control cost data. SCAC research has also enabled the joint cost-effectiveness analysis of emission reductions at sea and at land, and to check for effects on CO_2 emissions of implementing air pollution control technologies. Furthermore, SCAC research has contributed to monetization of damage costs for three health effects attributable to poor air quality.

A specific study has shown that the use of different climate metrics as indicators of climate change effects from emissions to the atmosphere does not significantly affect the results in terms of prioritised measures to reduce emissions. So the confusion induced by all the various climate metrics found in the literature is of little concern for prioritization of measures to control air pollutants with climate effects.

SCAC results also show that efficiency improvements, use of non-combustion energy sources and behavioural changes all ensure co-benefits between climate change and air pollution although some risks for trade-offs can be identified. First and foremost, the use of solid biofuels for electricity and heating can decrease CO_2 emissions but is at risk of increasing emissions of some air pollutants. Secondly, the use of flexible mechanisms such as the EU emissions trading system is at risk of geographically placing emission reductions in areas where air quality benefits are lower than what could have been achieved if considering also effects on air quality. Behavioural changes, even incremental ones, have both significant effects on emissions of air pollutants and imply co-benefits between climate change and air pollution.

3 Introduction

Collaborative and multi-disciplinary research on air pollution combined with extensive international collaboration and engagement in expert groups under international conventions has since many years been a successful approach to ensure the continuous development of the scientific basis as well as influence on the development of international agreements and policies. The Swedish Clean Air and Climate research program (SCAC) is the latest in a series of initiatives which have run more or less continuously since the end of the last millennium, most of them funded by the Swedish Environmental Protection Agency.

The SCAC research programmes´ first phase ended in March 2017. Well before the end of the first phase, a clear need for continued research on air pollution and climate was defined by the Swedish EPA. The main driver was the need for an extended scientific knowledge base in national and international discussions and negotiations on a development of new air pollution policies and measures. Specifically, the Swedish EPA identified the areas: air pollution and climate interactions and hemispheric transport; air pollution and human health with focus on particles from transport and domestic wood burning; ecosystem effects (and air pollution – climate interactions) of ozone and nitrogen, the latter with emphasis on national nitrogen budgets and biodiversity. Finally, integrated assessment modelling and identification of the most efficient abatement strategies was included.

These priorities formed the basis of the SCAC – Phase 2 program. SCAC 2 was launched as a smaller and more compact research program than SCAC phase 1, starting in April 2017 and ending in mid-2020.

The research performed in SCAC 2 has made it possible for the involved scientists to engage in many of the expert groups under the LRTAP Convention and also to interact cooperate with scientists from the climate and Arctic research communities.

4 Air pollution and climate interactions

Work package 1, WP1, in SCAC had three important goals: the first was to increase knowledge about hemispheric transport of air pollutants with emphasis on tropospheric ozone and particles. The second goal was to evaluate how regional emissions of air pollutants in Europe, and in other parts of the northern hemisphere, affect climate locally and remotely. The third goal was to ensure that information related to the first two goals is taken into account in the development of international agreements on air pollution emission reductions.

The first and second goals of WP1 are closely linked to the international evaluation of the impact of Short-Lived Climate Forcers (SLCFs) on climate in the Arctic organised by AMAP (The Arctic Monitoring and Assessment Program). AMAP's expert group for SLCF, in which researchers from WP1 participate, is working on a report to be published in 2021. As a part of the report, and related to the first goal of WP1, an evaluation of the performance of various models is carried out concerning the simulation of air pollution transport across the Arctic and the northern hemisphere. Here, scientists from WP1 contribute with model simulations using the atmospheric chemistry model MATCH, Multi-scale Atmospheric Transport and Chemistry model (Robertson et al., 1999; Andersson et al., 2007). Cloud properties simulated by climate models are also evaluated against satellite data. This will provide an updated picture of our ability to describe long-range transport of air pollution and climate in the Arctic. Most of the results linked to the AMAP report will be finalized in the end of 2020 and are therefore not reported here. However, we can present some results from new scenarios for future levels of ground-level ozone and $PM_{2.5}$ over the northern hemisphere based on state-of-the-art emission scenarios. Another important part of the AMAP report, and related to the second goal of WP1, is to evaluate simulations of how future global emission scenarios of air pollutants affect climate in the Arctic and in other parts of the world. Researchers from WP1 contribute to this work through coupled Earth system simulations with the Norwegian Earth System Model NorESM (Seland et al., 2020). Using NorESM we have within SCAC-2 also evaluated how altered emissions of sulphur and soot in major geographical regions affect climate. This work is a collaboration with CICERO in Norway and a continuation of studies initiated during SCAC-1. It has led to three scientific publications addressing the effect on the climate of sulphur and soot emissions and the resulting heat transport to the Arctic (Krishnan et al., 2020; Lewinschal et al., 2019; Sand et al., 2020).

The third goal of WP1 has been achieved by contributing to the work of different working groups within the LRTAP Convention. Researchers from WP1 have participated in a number of meetings within HTAP (Task Force for Interhemispheric Transport), TFMM (Task Force for Measurements and

Modelling) and TFIAM (Task Force for Integrated Assessment Modelling) during the period of SCAC and contributed with presentations of results from SCAC. Researchers in WP1 have also participated in the Eurodelta group and its activity EDTRENDS. The work there has been aimed at understanding uncertainties in models and their inputs and the results are described in a number of scientific publications (Ciarelli et al., 2019ab; Colette et al., 2017; Otero et al., 2018; Theobald et al., 2019; Vivanco et al., 2018).

4.1 Highlights from the research

The most important results from WP1 are the following. Further results linked to the AMAP report on SLCF will be finalized later in 2020.

- Reduced emissions of sulphur at mid-latitudes lead to increased heat transport in the atmosphere to the Arctic and an increased warming, while reduced emissions of black carbon lead to reduced heat transport and a cooling (Lewinschal et al., 2019; Sand et al., 2020; Krishnan et al., 2020).
- The impact on climate from emission changes of soot and sulphur in five different regions of the Northern Hemisphere has been quantified. The results indicate that in terms of their climate impact per unit mass, emission reductions of soot (reduced warming) result in a 3-5 times larger Arctic temperature change compared to sulphur (reduced cooling) (Lewinschal et al., 2019; Sand et al., 2020).
- The temperature change as a function of the change in particle or precursor emissions is non-linear. There is a greater temperature change at lower emission levels (Lewinschal et al., 2019; Sand et al., 2020).
- The annual average level of PM2.5 in background air in southern Sweden may decrease by about 10% in 2030 and about 15% in 2040 compared to 2020 based on IIASA's latest "current legislation" (CLE) emission scenario. The corresponding numbers for the "maximum feasible reduction" (SDS_MFR) scenario are 35 and 40% respectively. These changes are primarily due to emission reductions in Europe.
- The level of the April-September mean of the daily maximum ground-level ozone in background air in Sweden may decrease by about 6% in 2030 and about 9% in 2040 compared to 2020 based on IIASA's latest CLE emission scenario. The corresponding numbers for the SDS_MFR scenario are 20 and 30% respectively. For these changes hemispheric transport is more important than for PM.

4.2 Contribution to development of policies and measures

Researchers in WP1 have numerous links to international networks within the research community tasked with producing scientific evidence to support the development of useful and cost effective co-beneficial mitigation strategies for air pollution and climate change. The results from NorESM show how changes in particulate emissions in Europe affect climate with both warming and cooling. Along with similar studies with other climate models, a scientific basis for climate neutral air pollution measures is created within the framework of the LRTAP Convention and the EU. Similarly, the forthcoming AMAP report on SLCF and climate aims to provide scientific evidence for continued action in the countries of the Arctic Council. WP1 provides important contributions both with model simulations and model quality evaluation for reducing climate change in the Arctic but still with strong air quality improvements in the emission regions. The completion of the synthesis work within AMAP lies after the end of SCAC, but the work within SCAC has been crucial to our ability to make a significant contribution to the AMAP report.

When it comes to air quality in Europe, the work within TFMM and Eurodelta has shown that emission data for particles, and in particular condensable particles, need to be improved. Emission reductions over the past 25 years have had an effect on air concentrations and deposition in Europe and our national modelling tool MATCH for nitrogen, particle and ozone stands very well in comparison with other similar models in Europe (Colette et al., 2017; Theobald et al., 2019).

4.3 Results

4.3.1 Climate impact of sulphur and soot emissions

We used the Earth System Model NorESM (Seland et al., 2020), to calculate emission-to-temperature-response metrics for sulphur dioxide (SO_2) and soot emission changes in four different policy-relevant regions: Europe (EU), North America (NA), East Asia (EA) and South Asia (SA) (Lewinschal et al., 2019; Sand et al, 2020). The emissions in each individual region were increased to give approximately the same absolute global average radiative forcing change (~-0.45Wm^{-2} for SO_2 and below 1Wm^{-2} for soot). We found that changes of sulphur and soot emissions in different areas of the Northern Hemisphere (EU, NA, EA and SA) give similar temperature response per kilogram of emission change in different latitude bands (Southern Hemisphere, Tropics, Northern Hemisphere Mid-latitudes and Arctic) (see Figure 4.1).

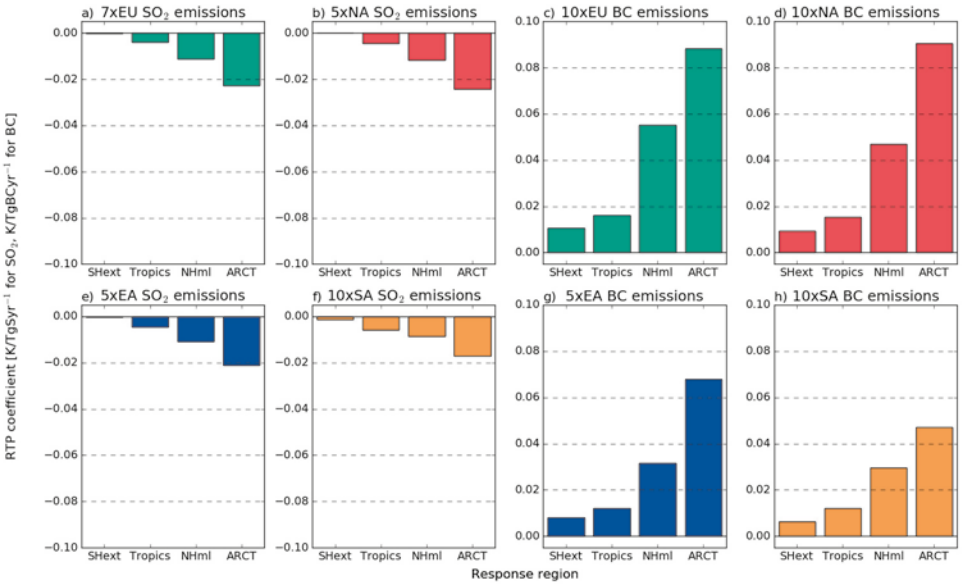


Figure 4.1. Left columns: Temperature change [K] per sulphur emission (Tg S) per year for the latitude bands (x-axis) of the southern hemisphere extra-tropics (SHext), the tropics (Tropics), the northern hemisphere mid-latitudes (NHml) and the Arctic (ARCT). The four sub-figures show the effect of emissions in Tg/yr in the regions, EU a), North America (NA) b), East Asia (EA)e) and South Asia (SA) f). The reference year is 2000 and sulphur emissions were increased 7 times over Europe, 5 times over North America, 5 times over East Asia and 10 times over South Asia (from Lewinschal et al., 2019). Right columns (c, d, g, h): same as in the left columns but for soot (Sand et al., 2020). Soot emissions have been multiplied by a factor of ten for all areas except East Asia where a factor of 5 has been used.

A very important result is that the temperature response in the Arctic is always largest, usually twice as large as in the emission region itself. It is also evident that the temperature response per unit emission in the Arctic is about a factor three to five higher for soot compared to sulphur. This result implies that even though the global average sulphur emissions are about ten times greater than soot emissions, a large part of the climate effect (warming) caused by a reduction in sulphur emissions, e.g. to improve air quality, can be compensated by a corresponding reduction in soot emissions (cooling). Preliminary (and yet unpublished) results also show that the temperature response from emission reductions in sulphur and soot are additive.

The temperature response for soot is non-linear in the Arctic, i.e. the temperature change per kilogram of soot becomes smaller if a large emission change is made - regardless of the emission region. For the mid-latitudes, the temperature change per unit emission over Europe is also non-linear. The same qualitative result is obtained for European sulphur emissions: the temperature change per kilogram of sulphur becomes smaller at high sulphur concentrations. This is because the indirect climate effect of the particles on clouds reaches a saturation effect at high particle concentrations.

Simulations reported in Krishnan et al. (2020) show that an increase in heat transport in the atmosphere from the middle latitudes to the Arctic is driving the higher temperature change in the Arctic compared to other areas.

The increased heat transport in the atmosphere initiates changes in the distribution of the Arctic sea ice and results in increased heat exchange between the sea and the atmosphere. Changes in heat transport in the ocean play a minor role and generally dampen the temperature response. The results show that it is important that models represent the heat exchange between sea and atmosphere correctly and it is especially important that sea ice changes and turbulent heat exchange are described as accurately as possible.

4.3.2 Interhemispheric transport of ozone and $PM_{2.5}$

Several new emission scenarios from IIASA based on the GAINS model (https://iiasa.ac.at/web/home/research/researchPrograms/air/Global_emissions.html) have been made available within the work on the AMAP report on SLCF. Here we analyse two of these scenarios, CLE and SDS_MFR and what they could mean for the air quality in background air in Europe and Sweden. CLE refers to ECLIPSE_V6b_CLE_base where CLE (Current LEgislation) represents a successful global implementation of the latest legislation and technology to reduce emissions of air pollution. CLE includes current and planned environmental laws, considering known delays and failures up to now but assuming full enforcement in the future. In addition, the MFR_SDS scenario (ECLIPSE_V6b_SDS_MFR) adopts a strict policy requiring the introduction of best available technology for all economic activities that generate emissions of air pollution combined with measures to achieve the global sustainability goals and the Paris Agreement. The measures are based on the information available in GAINS today, which can be seen as a conservative scenario where no further technological development is assumed. On the other hand, it is an optimistic scenario because it assumes that all technologies deliver the emission reduction for which they are designed and that they are fully implemented without regard to costs. However, technical life is taken into account, i.e. no early scrapping of equipment has been assumed.

Figure 4.2 shows calculated annual mean concentrations of $PM_{2.5}$ in background air from MATCH for CLE in 2020 and 2040 and SDS_MFR in 2040. Both CLE and SDS_MFR would result in substantial reductions of $PM_{2.5}$. For CLE, however, areas with increases in southern Asia and the Middle East are also seen, whereas reductions are seen elsewhere. Reductions in China are most evident, but also in Europe. For SDS_MFR there are reductions throughout and very large reductions in Asia. The bar graphs show how much the annual average surface concentration of $PM_{2.5}$ in background air is reduced in southern Sweden and the contribution to the reduction from different geographical areas for every ten years between 2020 and 2050. Overall, the average concentration of $PM_{2.5}$ in background air over southern Sweden could decrease by about 10 % in 2030 and by about 15% in 2040 compared to 2020 in CLE and by 35 and 40% respectively in SDS_MFR. The reductions in $PM_{2.5}$ across Sweden are mainly a result of reduced emissions in Europe. Reduced interhemispheric transport from North America and Asia makes a small contribution, up to a few percent. This is in line with previous results from HTAP1 and HTAP2 e.g. Liang et al. (2018) that for particles, emission reductions in the nearby area are most important. The contribution from Russia is greater because this is the closest region.

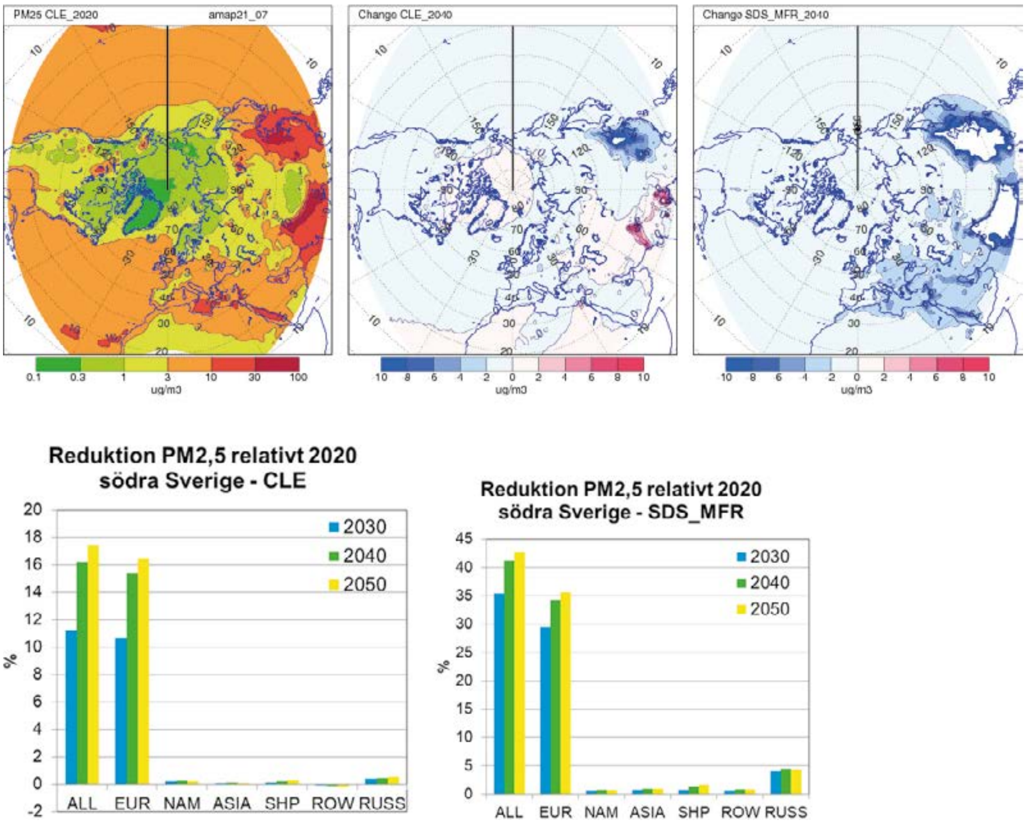


Figure 4.2. Simulated background surface concentrations of PM2.5 over the northern hemisphere for different emission scenarios. Top left - total annual average concentrations for CLE 2020, in the middle change between 2020 and 2040 in the CLE scenario and to the right corresponding change in the SDS_MFR scenario. The bar charts show relative changes in the annual mean concentration of PM2.5 over Götaland and Svealand for different time periods for CLE (left) and SD_MFR (right). The bars refer to contributions from Europe except Russia (EUR), the USA and Canada (NAM), South and East Asia (ASIA), ship traffic (SHP), Russia (RUSS) and the rest of the world outside these areas (ROW). Note that the reductions for SDS_MFR in China and India go beyond the scale in the figure at the top right. The attribution of the contributions to changes from different source regions were calculated by changing all the anthropogenic emissions (SO_2, NOx, CO, NMVOC, BC, OM, dust) at the same time until 2030, 2040 and 2050 for each region individually and adjusting the methane concentration as well according to the methane emission changes by region.

Figure 4.3 shows the corresponding results for ground-level ozone in background air. Here, results are presented for the mean of the daily maximum concentrations (MDM) during the ozone season (April-September). As for $PM_{2.5}$, both CLE and SDS_MFR would mean significant reductions in ground-level ozone. For CLE, however, areas with increases in South Asia and the Middle East are also seen, whereas there are reductions in all other areas. For SDS_MFR, there are reductions throughout and very large reductions in all densely populated regions. The bar charts show how much MDM for ozone is reduced on average for the whole of Sweden and the contribution from different geographical areas. Overall, MDM in background air in Sweden could decrease by about 6% in 2030 and by about 9% in 2040 compared to 2020 in CLE and by 20 and 30% in SDS_MFR, respectively. For ground-level ozone, the reductions in Sweden are largely due to decreasing emissions throughout the Northern Hemisphere and for SDS_MFR, the contribution from regions other than Europe is greater than 50%. This difference in the importance of interhemispheric transport between $PM_{2.5}$ and ground-level ozone is in line with previous results from HTAP1 (2010) and HTAP2 (Jonson et al., 2018).

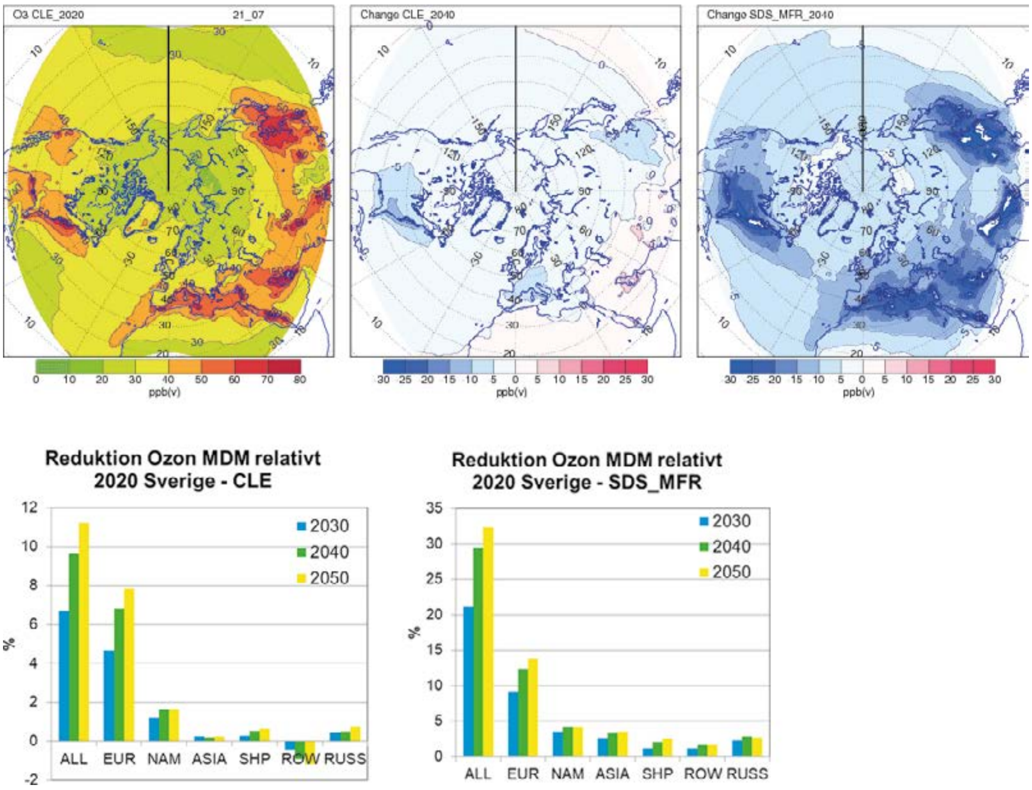


Figure 4.3. As Figure 4.2, but for background levels of ground-level ozone, mean of daily maximum (MDM) for April-September. Top left total mean levels for CLE 2020, in the middle change between 2020 and 2040 in the CLE scenario and to the right corresponding change in the SDS_MFR scenario. The bar charts show relative changes in MDM across Sweden for different time periods for CLE (left) and SDS_MFR (right). Note that the reductions for SDS_MFR go beyond the scale in the figure at the top right in several regions in Asia. The attribution of the contributions to changes from different source regions were calculated by changing all the anthropogenic emissions (SO_2, NO_x, CO, NMVOC, BC, OM, dust) at the same time until 2030, 2040 and 2050 for each region individually and adjusting the methane concentration as well according to the methane emission changes by region.

4.4 Methods

In SCAC-WP1, two different numerical models have been used; the Earth System Model NorESM (Seland et al, 2020) and the atmospheric chemistry model MATCH (Robertson et al., 1999; Andersson et al., 2007). NorESM is an Earth system model with linked descriptions of the three spatial dimensions of the atmosphere, land, ocean and sea ice. The model also has an interactive description of atmospheric chemistry and particle chemistry and physics. With NorESM, time-dependent simulations are made of how different aspects of the climate such as temperature, sea ice and rainfall are affected by historical and future emissions of greenhouse gases and SLCFs. The connection between the different sub-components is dynamic. Simulations with NorESM require considerable computational resources and the horizontal geographical resolution is therefore limited to about 200´200 km^2. MATCH is a regional atmospheric chemistry model, CTM, which, in addition to atmospheric chemistry for particles, also includes chemistry for ozone and other gaseous air pollutants. MATCH simulates time-dependent concentrations and deposition of various air pollutants in three spatial dimensions. MATCH cannot dynamically simulate the climate, however, the impact on cloudiness and radiation balance can be calculated through a one-way link with the regional climate model RCA4 (Thomas et al., 2015). MATCH can be run with a higher geographical resolution, 75´75 km^2, and with observed meteorology to study long-range transport of air pollution to the Arctic.

5 Human health impacts from air pollution

5.1 Highlights from the research

The results within SCAC support recent reports that when using particle matrices that are determined by the concentrations resulting from local sources such as traffic, the relative risk increase per increased concentration will be higher than otherwise. This applies, for example, to the relation of exhaust particles with mortality and to the relationship between soot from exhaust gases and stroke.

The importance of local particle sources for the increase in risk means that health effects occur at levels not only below the environmental quality standards for PM_{10} and $PM_{2.5}$, but even under the Swedish specifications of the environmental quality targets.

The new knowledge on exposure-response relationships shows that health impact calculations based on older assumptions significantly underestimate potential health benefits with reduced exposure to local sources such as urban car traffic.

High correlation between several types of pollutants, including exhaust particles, nitrogen dioxide and road dust, complicates the interpretation of the results in studies from a single environment and motivates further research where the effect of different pollutants is studied in several different environments with different correlations between levels.

5.2 How can these results contribute to development of policies and measures?

One issue within SCAC has concerned how the effectiveness of various measures to reduce the health consequences of the particles depends on the measures of exposure and exposure response functions adopted in health consequence calculations. This has a huge impact on cost-benefit calculations and rationale for decisions. For risk assessments and health impact assessments, it is crucial to know all most significant health effects of pollution. Specifically, for the particles, in contrast to gases with similar composition everywhere, it is necessary to know whether their origin and properties affect the health effects they cause.

Several conditions justify the investigation of particle health effects in Sweden, despite the fact that we have low levels of pollution in an international comparison. The fact is that unusually low levels are a motive for the studies, as studies in recent years indicate that differences in exposure at low levels are not only significant from a health point of view but may also give greater relative changes in risk per concentration change than at higher concentrations. The composition of the particle fractions also differs between countries, in Sweden studded tires are allowed which give more wear particles. Another motive for epidemiological studies of the effects of air pollution in Sweden is that we have exceptionally good conditions for population studies thanks to our personal identification numbers, population registers, uniform health care and comprehensive health registries.

SCAC has included studies of the relationship between exposure to different types of particles and the risk of specific health effects, and literature reviews focusing on road wear dust and wood smoke, problems that are of greater relative importance in Sweden than in many strong research nations such as the United States. Within SCAC, health impact assessments have also been performed to elucidate how crucial for the conclusions it is to use relevant exposure-response assumptions for different types of particles. Since the health impacts of air pollution are strongly dominated by deaths, regardless of whether health costs or loss of disability adjusted life years are calculated, sensitivity in the calculations of mortality effects is central.

For nearly 20 years, health impact calculations for $PM_{2.5}$ and mortality have been dominated by results from the very large American Cancer Society Prevention Study II (ACS CPS II) cohort study, where air pollution studies are initially based on between-city comparisons (assume same exposure for all inhabitants). Based on that study, 6% higher mortality per 10 $\mu g/m^3$ higher annual mean of $PM_{2.5}$ has almost become a standard. This large study influenced the weighted coefficient in a review (6.2% per 10 $\mu g/m^3$) selected in WHO's Impact Assessment Report (WHO 2013). Therefore, most calculations have, regardless of sources and spatial resolution, assumed that $PM_{2.5}$ gives about 6% higher mortality per 10 $\mu g/m^3$. For at least 15 years, it has been discussed that primary particles from local sources should lead to greater risk increase per elevated mass concentration than the regional background content dominated by secondary formed and aged particles. Therefore, sometimes the impacts of traffic pollution have been calculated based on NO_2 or NO_x as the exposure measure. It has also been reported for almost 10 years that soot particles give higher increase in risk per increased mass concentration. A recent study with higher spatial resolution, but based on ACS, reported more than six times higher risk increase per levels of the local contribution of $PM_{2.5}$ than for the regional background levels, 26 and 4% per 10 $\mu g/m^3$, respectively. The significance of the difference for Swedish conditions has been emphasized in the recent health impact assessment in SCAC. The rational for applying the high coefficient of the local gradient (the "inner city variation") recently reported for ACS is substantiated by several recent studies. A meta-analysis from 2018 found that 11 studies with an average exposure below 10 $\mu g/m^3$ gives a weighted estimate of 24% per 10 $\mu g/m^3$. A large-scale US study published in 2019 found close to 30% increase per 10 $\mu g/m^3$ for the local contribution of $PM_{2.5}$. A new Danish study reported 22% per 10 $\mu g/m^3$ $PM_{2.5}$ and no effect of secondary inorganic fraction, i.e. ammonium, nitrate, sulphate etc.

The mortality analyses compiled for the SCAC cohorts also give high coefficients in relation to local traffic-related particles, which indicates that it is inappropriate to use the WHO recommendation (HRAPIE, WHO, 2013) when assessing the impact of local traffic-related particles on mortality. In 2019 The Swedish Transport Administration accordingly revised their model (ASEK) for impacts and health costs.

5.3 Results

5.3.1 Cardiovascular disease

Within SCAC, one of the aims was to study source-specific effects on the risk of stroke and ischemic heart disease (mainly myocardial infarction) based on modelled concentrations of exhaust gas and wear particles from traffic, particles from residential heating etc in three Swedish regions. The included studies have followed up a large number of people for many years in the Stockholm, Gothenburg and Umeå regions. A total of 5166 new cases of ischemic heart disease and 3119 of stroke are included in the study comprising all three regions.

Already in the initial analysis based on the participants in the Gothenburg study, a relationship was found between the total exposure level of $PM_{2.5}$ over the past 5 years and new cases of ischemic heart disease (Stockfelt et al, 2017). In the aggregate analysis for all cohorts, few consistent patterns were observed between the exposure variables and the cardiovascular outcomes, which could be due to the fact that only the ambient concentrations at the residential address could be taken into account. The risk of contracting stroke was increased by 4% (95% CI 0.4-8.0%) for every increase in the same year's levels of soot (black carbon) at the dwelling corresponding to the interquartile range of 0.3 $\mu g/m^3$ (Ljungman et al, 2019). The soot exposure had a range of 0.01–4.6 $\mu g/m^3$. A similar risk increase was seen for the exposures averaged over the preceding 1-5 and 6-10 years but did not reach statistical significance. For soot from exhaust gases, the risk increase was also significant in relation to the previous 1-5 years of exposure. For ischemic heart disease, the association was only significant in relation to the same year's PM_{10} exposure from home heating, most evident in Umeå, where high quality emission data are available based on property data from the chimney sweepers.

5.3.2 Pulmonary Disease

For over 5,000 people from the Gothenburg area who are part of a cohort study on lung function, the exposure to air pollution at the residence has been calculated using the modelling in SCAC. Exposure to PM_{10}, $PM_{2.5}$ and soot BC) from traffic showed small but statistically significant effects in the form of reduced maximum exhaled flow and vital capacity (Carlsen et al, 2020).

5.3.3 Mortality

The same cohorts used to study cardiovascular disease have also been used to investigate how mortality is affected by particle levels at the residence

(Sommar et al, 2020). In general, the analyses showed a clear link with particles from traffic and the absence of association with particles from residential heating. Exposure to traffic-related particles was associated with high relative risks, for example as PM_{10} including the wear particles 8% higher mortality per increase of 4 µg/m^3 in the time window of the previous 6-10 years (Sommar et al, 2020). For the same time window and only the exhaust particles with a lower exposure level, the combined risk estimate was 7% (95% CI 2-12%) per increase of 0.6 µg/m^3 (cohort-specific results are presented in to figure 5.1).

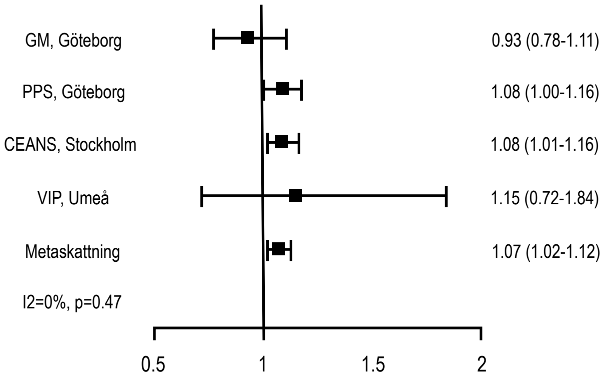


Figure 5.1. Exposure to exhaust particles and HR for natural death per 0.6 µg/ m3 with 95% confidence interval.

5.3.4 Birthweight

SCAC has included a registry-based study of birth outcomes in relation to calculated levels of exhaust gas particles at the mother's residence during pregnancy. The study comprises 26 municipalities within Greater Stockholm and almost 187,000 children born in 2003-2013 (Olsson et al, 2020). Exposure to exhaust particles generally increased with increase in socioeconomic status, for example by 69% between the shortest and the longest education category, which might hide harmful effects of the particles since the birth outcome is generally more favourable in groups with high socioeconomic status.

Exposure during pregnancy had a range of 7-854 ng/m^3 for exhaust particles, the mean was 202 and the interquartile range 209 ng/m^3. There was a statistically significant relationship between reduced birth weight and particle concentration during the 1st and 2nd trimesters, as well as the average exposure levels throughout pregnancy (Figure 5.2). The effect of minus 7.5 g (95% CI -12.0; -2.9) for an increase corresponding to the interquartile range is in line with minus 9 g for 200 ng/m^3 of increase in elemental carbon exposure levels recently demonstrated in a study from Massachusetts, USA. Higher levels during pregnancy in the Stockholm study also increased the likelihood for the child to belong to the lowest 10% weight category (Small for Gestational Age, SGA) in relation to the length of pregnancy.

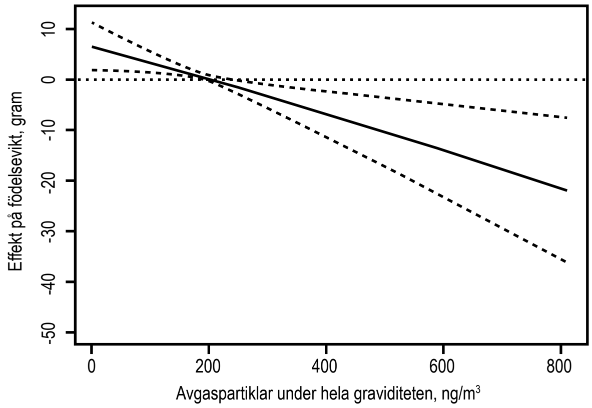


Figure 5.2. Birth weight dependence on the levels of exhaust particulate exposure during pregnancy (with 95% confidence interval) compared to the mean after adjustment for all other factors.

5.3.5 Literature study on road dust

A literature review on health effects of road dust particles within SCAC shows that a large number of epidemiological studies have found a link between short-term exposure to coarse particles (2.5-10 µm) and increased number of hospitalizations for respiratory and cardiovascular diseases and increased total mortality. A weighted result from 8 studies shows statistically significant increased overall mortality by 0.3 percent, increased death in respiratory disease by 0.5 percent, and increased cardiovascular disease death by 0.03 % in relation to a 5 µg/m^3 increase in the daily mean PM$_{2.5\text{-}10}$. The results for hospital admissions showed that an increase in coarse particle exposure level by 5 µg/m^3 was associated with a statistically significant increase in acute hospital admissions by 1% for the respiratory conditions and 0.1% increase in admissions for cardiovascular disease. Considerably fewer studies have analysed long-term effects of coarse particles on mortality and their combined results could not show any statistically significant impact.

In recent years, several large and well-conducted studies from North America and Europe have been published that have consistently shown the negative impact of exposure to coarse particles on pregnancy outcomes, mainly low birth weight. Aggregated results from 3 studies have shown reduced birth weight by 4.2 grams per 5 µg / m^3 increase in PMcoarse exposure averaged throughout pregnancy.

The results on long-term effects of coarse particles on cardiovascular health were not distinct. There are several studies, mainly from the US and China that have shown association with asthma related symptoms in children, while no effect was seen in corresponding European studies. Even for many other health outcomes, the existing evidence is too limited for drawing firm conclusions.

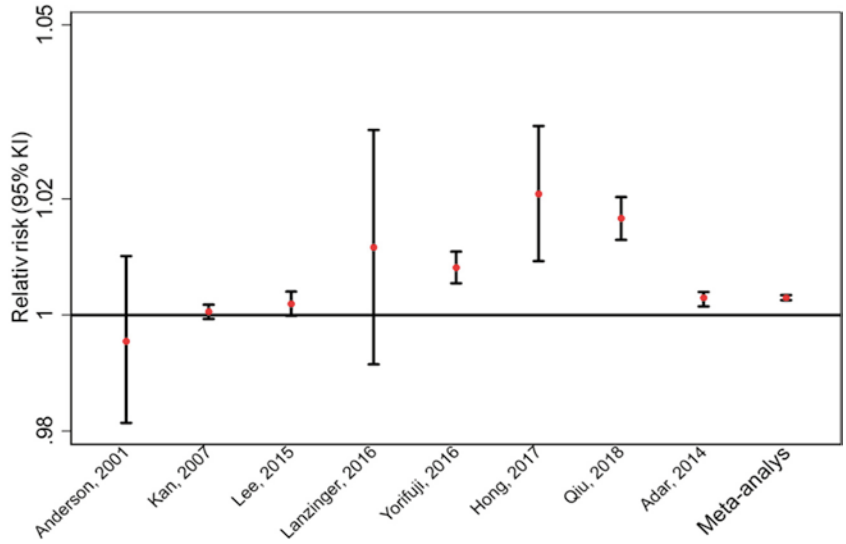


Figure 5.3. Short-term exposure to PM2.5–10 and total mortality, RR expressed per 5 µg/m3 increase in exposure levels with 95% confidence interval.

Although the exact causal pathways are not fully understood, it has been suggested that coarse PM contains several redox-active metals, including Fe, Cu, Cr, Ni, and Mn, which can induce the generation of reactive oxygen species (ROS) within cells, leading to oxidative stress, inflammation, and as a result produce adverse health effects. With regard to pregnancy outcomes, animal studies found that PM$_{2.5\text{-}10}$ induced pulmonary inflammation may alter blood viscosity leading to placenta vascular dysfunction.

The correlation between the different particle metrics within study areas was highly variable across studies. Most often adjustment for PM$_{2.5}$ resulted in weaker and less precise effect estimates, although the direction of associations with coarse PM concentrations remained unchanged. However, not all of the included studies explored multi-pollutant models or provided information on correlation between pollutants.

5.3.6 Literature study on wood-smoke

In SCAC, a literature review on the health effects of particulate matter in wood-smoke has been performed. A total of 11 studies on mortality were included, of which 8 relate to short-term effects and used several different particle indicators: PM10, PM2.5, PM2.5 from wood etc., which complicates combined analyses of the results. Most often, an increase in daily deaths is about 1-3 percent per 10 µg/m3 PM2.5 or PM10 or for an increase corresponding to the interquartile range of exposure, with a slightly stronger effect on cardiovascular and respiratory mortality. The increase appears to be higher than what is typically seen for PM2.5. One explanation could be that local combustion particles are more harmful than the secondary fraction in background levels of PM2.5. Only three studies included long-term effects on mortality, an ecological intervention study, a cohort study of COPD patients and a study of female school employees. The latter found that the level of potassium, a marker for wood burning, was strongly associated with mortality. However, general conclusions are difficult to draw from these studies.

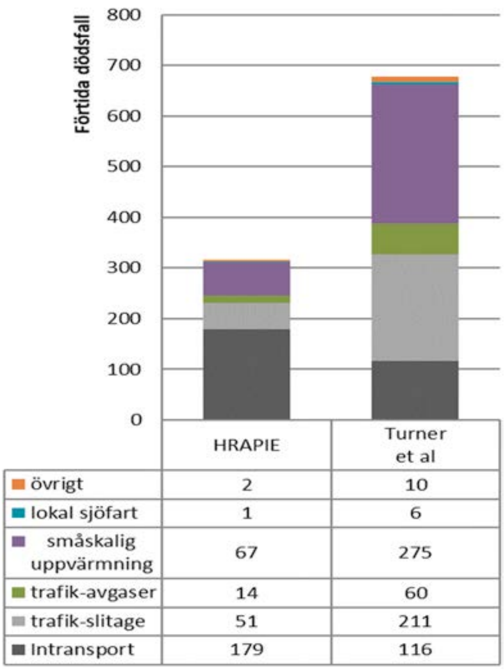
15 of the studies deal with daily number of hospitalizations or emergency visits, of which 13 are for respiratory conditions and 7 for cardiovascular disease. For the respiratory conditions, the number of cases per 10 µg/m^3 $PM_{2.5}$ increases by 1-19% in various studies, usually about 6-8%, and typically 1-2% per 10 µg/m^3 higher level of PM_{10} dominated by wood burning particles.

Other outcomes examined in the included studies are respiratory illness and medication use, development of dementia and birth outcomes, primarily lower birth weight, where four out of five studies found statistically significant effects.

5.3.7 Source-specific health impact calculations

The significance of the choice of exposure measures and exposure-response functions for health impact assessments has been investigated in two studies within SCAC. In Sweden, transported air masses account for a large part of the population exposure for $PM_{2.5}$: 64, 70 and 73% in Gothenburg, Stockholm and Umeå, respectively, according to the modelling in SCAC. This corresponds to about half of the deaths attributed to $PM_{2.5}$ in these cities, if they are based on earlier mentioned between-city comparisons in the US ACS cohort, or if the WHO recommendation of 2013 is used where a weighted exposure-response relationship regardless of source is employed, and no effect is assumed for concentrations below background levels of up to 2 µg/m^3 (Segersson et al, 2017). The European Environment Agency (EEA) gives even greater weight to the regional background level of $PM_{2.5}$ as calculations are performed with 6.2% per 10 µg/m^3 regardless of source, and does not include a threshold at 2 µg/m^3. When studying local differences in $PM_{2.5}$ in Los Angeles County based on 23 measurement stations in the ACS cohort, 17% higher mortality per 10 µg/m^3 was found, and this is assumed to be 2-3 times greater for locally produced $PM_{2.5}$ than the importance of regional background to mortality (Segersson et al, 2017).

It is important to consider new evidence and when suggested update the ER-functions applied in impact assessments, e.g. the GEMM risk functions as an improvement of the Global burden of disease study. With later studies of both local contributions and regional backgrounds of $PM_{2.5}$ and mortality, the importance of the local sources in the health impact calculations increases. A recent study from the US based on the ACS cohort modelled the levels at residence and separated the effects of local and regional levels. For the regional background level of $PM_{2.5}$, mortality increased by 4% per 10 µg/m^3 and for the local contribution - by 26%. In a sensitivity analysis for the Greater Stockholm area, a comparison of the alternatives to applying the same exposure-response relationship for long-range transported PM2.5 and for local sources according to WHO (HRAPIE, WHO, 2013) with applying the relationships from the aforementioned ACS analysis. The large differences in the number of deaths attributed to different sources are illustrated in Figure 5.4 (Segersson et al, 2020).



	HRAPIE	Turner et al
🟧 övrigt	2	10
🟦 lokal sjöfart	1	6
🟪 småskalig uppvärmning	67	275
🟩 trafik-avgaser	14	60
▨ trafik-slitage	51	211
■ Intransport	179	116

Figure 5.4. Sources of significance for number of deaths / years in Stockholm with RR from HRAPIE and ACS with high spatial resolution (Turner et al. 2016). (Caption categories: övrigt = other; lokal sjöfart = local shipping; småskaliguppvärmning = small-scale heating: trafik-avgaser, -slitage = traffic – exhaust, - road wear; intransport – transport from outside study area)

5.4 Methods

The epidemiological studies of particle exposure and health impact calculations within SCAC are based on the model calculations performed, where local emission data from the period 1990-2011 were used together with established emission factors, meteorology and trends in concentrations (Segersson et al, 2017).

Incident cases of stroke and ischemic heart disease, as well as total and cause-specific mortality, have been studied based on the same follow-up studies. SCAC includes two cohorts from Gothenburg (The Primary Prevention Study, PPS, and Gothenburg's MONICA cohort (Multinational Monitoring of Trends and Determinants in Cardiovascular Diseases). From Stockholm, the Cardiovascular Effects of Air Pollution and Noise Study (CEANS) has been included, which is based on participants from four studies: Stockholm Diabetes Prevention Program (SDPP), 60-year-olds (60YO), Stockholm Screening Across the Lifespan Twin study and TwinGene (SALT) and Swedish National Study on Aging and Care (SNAC). The data for the Umea region comes from the Västerbotten Intervention Program (VIP).

The study of air pollution exposure levels and incidence is based on cohort-specific analyses where results have been weighed together in a meta-analysis (Ljungman et al, 2019). In all participating studies, the participants were examined at the inclusion in the original studies, and not included in the analysis of air pollution exposure and risk of illness / death if the disease had already developed at the time of enrolment. New cases have been identified through coordination with the National Board of Health's Patient and Death Cause Register.

After tracking of residential addresses and geocoding, exposure levels at home have been calculated for different time periods and the risk for considered health outcomes in relation to the average exposure during different time windows (the same year, 1-5 years earlier, 6-10 years earlier) has been analysed.

The same annual exposure data and similar statistical analyses have been used in the mortality studies. The adjustments for other risk factors were harmonized as much as possible between the cohorts, including gender, calendar year, smoking, alcohol consumption in Stockholm and Umeå, physical activity, marital status, socio-economic index through occupation, education, current employment and average income (Sommar et al, 2020). Cardiovascular risk factors such as BMI, diabetes, blood fats and high blood pressure were seen as possible mediators between air pollution exposure and mortality, and therefore no adjustment was made for these factors in the analyses.

In the registry-based cohort for the study of birth outcomes, data on the mother, pregnancy and child were retrieved from the Medical Birth Register, and information on the mother's and father's education, income, living conditions and housing address comes from the register at Statistics Sweden (Olsson et al, 2020). The analyses of air pollution effects took into account a number of factors such as maternal health, smoking habits, BMI, as well as various socio-economic conditions. Besides concentrations of exhaust particles during 1st and 2nd trimesters, as well as averaged throughout pregnancy, the ozone exposure at the home address has also been calculated.

SCAC's review of epidemiological literature on health effects related to exposure to road dust is based on 89 scientific articles published until last June 2018 (Gruzieva et al, 2020). Exposure indicators are focused on the coarse fraction of particles, $PM_{2.5\text{-}10}$. Most often, studies calculated this exposure indirectly, i.e. PM_{10} minus $PM_{2.5}$.

For the literature review on the effects of wood burnings, according to an established protocol, epidemiological studies from 1995-2018 were included after searching in Pub Med and Web of Science (Forsberg et al, 2020). Finally, after reviewing, 46 scientific articles are included in the overview, many of which are from North America. They either indicate wood burning as a predominant source of studied particle content, use a calculated source-specific particle level or are based on the concentration of some indicator of the woodburning such as potassium.

6 Air pollution and ecosystems - ozone and nitrogen

The objectives of this SCAC work package were to answer the following research questions:

- What are the effects of ground-level ozone on the growth and carbon sequestration of temperate and boreal forests in northern Europe?
- Are there increasing risks for ozone impacts on sub-arctic vegetation due to high spring ozone concentrations in relation to the start of the growing season, which may be shifted by climate change
- What are the long-term effects of nitrogen deposition on biodiversity and ecosystem services in Northern Europe?

The following describes a selection of the results achieved.

6.1 The formation of ground-level ozone

Ozone in the air layers closest to the ground causes significant damage to vegetation, human health and materials and is also an important greenhouse gas. Ozone in the troposphere is formed though chemical reactions driven by the energy from sunlight involving ozone precursor substances: volatile organic compounds and nitrogen oxides, the latter emitted mainly from traffic and industrial activities. Therefore, ozone formation is affected by the presence of its precursors as well as weather conditions, and is thus dependent on changed pollutant emissions and changed climate. Tropospheric ozone concentrations at northern latitudes depends, to a large extent, on emissions of ozone precursors over the entire northern hemisphere.

6.2 Highlights from the research - ozone

- A hot and dry summer, such as that in 2018, resulted in higher ozone levels in southern Sweden compared to what would otherwise have been the case, all else constant (Johansson et al., 2020)
- The start of the thermal growing season, based on air temperature, occurs earlier in the year in Sweden albeit with strong interannual variations (Andersson et al., 2020; Karlsson et al., 2020a).
- The highest ozone concentrations occur at earlier dates in the year towards the north and this “spring peak” forms a larger part of the annual ozone exposure with increasing latitude. The “spring peak” ozone increases in amplitude and shifts towards earlier in the year during 1990-2013 (Andersson et al., 2017; Klingberg et al., 2019; Andersson et al., 2020).
- Although Swedish ozone concentrations have decreased in summer, in northern Sweden the spring-time concentrations have risen and occur

earlier in the year. This pattern of development is due to decreasing precursor emissions in Sweden and Europe, increased Asian emissions impacting through inter-continental transport, and a changed climate (Andersson et al., 2017). The last includes increasing ozone uptake to vegetation in May, which could result in larger impacts, due to the earlier start of the growing season. In total this has led to a *decreased* overlap between spring peak ozone and the growing season in Sweden, but it remains a question whether the actual springtime impact on vegetation has changed over time (Andersson et al., 2020).

- An evaluation of the state of knowledge indicated that the risk of significant and lasting negative impacts on the vegetation in northern ecosystems is limited and, in any case, not greater than in southern Fennoscandia. Decision-making measures that reduce emissions of ozone-forming substances are also likely to protect vegetation in northern Fennoscandia (Karlsson et al., 2020a).
- The annual stem growth of spruce forests in southern Sweden is significantly negatively associated with the number of days of drought during the growing season, while there is an indication of positive association with high nitrogen deposition and temperature. The study showed no association of stem growth with ozone exposure or growing season onset. A substantially larger data set would be required in order to detect the effects of ozone and nitrogen on tree growth in Sweden with statistical significance (Karlsson et al., 2020b).

6.3 Contributions to the development of regulations - ozone

We have participated in the annual meetings of the Task Force for Measurement and Modelling (TFMM) under UNECE CLRTAP, contributing with knowledge and presenting results from the SCAC research. Furthermore, under the umbrella of TFMM we have engaged in EuroDelta trends (EDTRENDS). This is a multi-model experiment of air quality hindcasts, designed to facilitate a better understanding of the evolution of air pollution and its drivers over the period 1990-2010 in Europe. This international collaboration has resulted in improved understanding of major uncertainties (e.g. dry deposition, condensable organics and emissions of organics), sensitivities of ozone and deposition to climate and emission precursor changes (Colette et al., 2017; Vivanco et al., 2018; Otero et al., 2018; Theobald et al., 2019; Ciarelli et al., 2019a; Ciarelli et al., 2019b) and development of chemistry transport models, such as the Swedish MATCH model (a member of the Copernicus Atmospheric Monitoring Services providing forecasts and analysis of air pollution operationally, http:// https://atmosphere.copernicus.eu/; Marécal et al., 2015), the MATCH-Sweden system (providing national measurement and model fusion products of total atmospheric nitrogen and ozone deposition, MMF-TDEP, operationally; Andersson et al., 2017; Andersson et al., 2018), and the European community model, EMEP. We have also participated actively in ICP Vegetation and contributed to the development of methods and critical levels for risk assessment of ozone effects on vegetation included in the CLRTAP convention Mapping Manual, chapter 3 (Nov 2017). Furthermore, in connection with the Mapping Manual, we have contributed to the Scientific Background Document B, chapters 5, 7, 8 and 10.

Emission reductions of ozone precursors in Sweden and Europe since the 1980s have resulted in reduced ozone concentrations throughout the summer in Sweden (Andersson et al., 2017; Colette et al., 2017). It is important to continue to reduce emissions of ozone precursors, both nationally, in Europe and globally, to prevent a continued rise in the hemisphere background concentrations of ozone. Our results also show that increased air temperatures and reduced rainfall may lead to a climate penalty in air quality in Sweden, i.e. the expected decrease in ground-level ozone due to emission reduction is not fully achieved for instance during the dry and hot summer of 2018 (Johansson et al., 2020). Thus, the efforts we take to control ozone precursor emissions can at least partly be counterbalanced by climate change. However, based on realistic scenarios for the development of precursor emissions and the climate change effect on ozone levels, the effect of precursor emissions have been assessed to be of considerably larger importance in general than that of climate change. Furthermore, measures to decrease greenhouse gases globally, such as methane, will also reduce ground-level ozone.

A synergistic effect of reducing ozone levels near the Earth surface, both in terms of phytotoxic effects on agricultural crops and forests, and on human health in combination with the negative impact of ozone on the carbon balance of the world’s forests, provides strong motivation to further reduce emissions of ozone precursors. The extensive carbon accumulation that occurs in Swedish forests today would probably have been even higher in the absence of the current ozone exposure. However, a central question in this context is whether adult trees in forest stands are affected as much as young trees under experimental conditions. An attempt to answer this question based on growth measurements at spruce forests in southern Sweden showed that a data material from a very large number of sites is required to answer this question in a statistically reliable way.

6.4 Results - ozone

A changed climate affects both the formation of ground-level ozone in the air and the potential for effects of ozone on vegetation through leaf ozone uptake. A hot and dry summer, such as in 2018, resulted in higher ozone concentrations in southwestern Sweden than expected from normal emission levels, i.e. a climate penalty. In a study based on hourly ozone measurements in Western Sweden in 2018, compared with the five previous years 2013–2017 (Johansson et al., 2020), we were able to show that elevated ozone concentrations in 2018 could be linked to a combination of higher air temperatures and low precipitation, where the latter is likely to cause the vegetation to absorb less ozone than it would otherwise have. This is in line with model studies on the relationship between climate change and ground-level ozone in central and southern Europe (e.g. Andersson et al., 2007; Andersson and Engardt, 2010; Langner et al., 2012). Furthermore, higher air temperatures and less precipitation could reduce leaf ozone uptake by closing the stomata and hence reduce the ozone dose absorbed by plants (Mapping Manual, Chapter 3)

The research conducted within SCAC has addressed the research question whether there is an increased risk in terms of rising ozone levels and the exposure of vegetation to ozone in northern Sweden, in relation to the transport of ozone-forming substances throughout the northern hemisphere by inter-continental transport and a changing climate. Increasing air temperatures have led to the growing season starting earlier in the year during the period 1990 - 2013, especially in northern Sweden (http://www.smhi.se; Andersson et al., 2017; Andersson et al. 2020; Karlsson et al. 2020a). This also applies to specific calculations for birch trees, while for spruce forests the start of the growing season has not changed over recent decades (Karlsson et al., 2020a; Andersson et al., 2020). The spring peak in ozone has shifted to earlier in the year, more rapidly than the change in the date for the start of the growing season, now occurring earlier than the growing season onset. Thus, the overlap between the spring peak and the growing season has decreased over time since the 1990s (Andersson et al., 2020). However, additional work is needed to understand the trend in ozone uptake to the plants in spring and early summer at northern latitudes.

The highest ozone levels in northern Europe occur during spring, earlier in the year the farther north you come (Figure 6.1A). This was obvious from an analysis of latitude dependence on the occurrence of ozone and its distribution during the year based on data from 25 EMEP measurement stations for ozone north of the Alps and up to Northern Norway (Klingberg et al., 2019).

The ozone levels in Sweden and Norway were analysed for the period 1990–2013 by using the MATCH Sweden reanalysis (fused model and measurement data; Andersson et al., 2017). The high ozone levels in the spring showed an increase over time in northern Sweden. This change in spring ozone levels is caused by a combination of increased background levels of ozone throughout the Northern Hemisphere, reduced European and Swedish emissions, changes in the climate, as well as an increased dry deposition due to less snow and / or cold in May (Figure 6.1B, Andersson et al., 2017; Andersson et al., 2020). The last could result in larger impacts, due to the earlier start of the growing season. In total this has led to a *decreased* overlap between spring peak ozone and the growing season in Sweden, but it remains a question whether the actual springtime impact on vegetation has changed over time (Andersson et al., 2020).

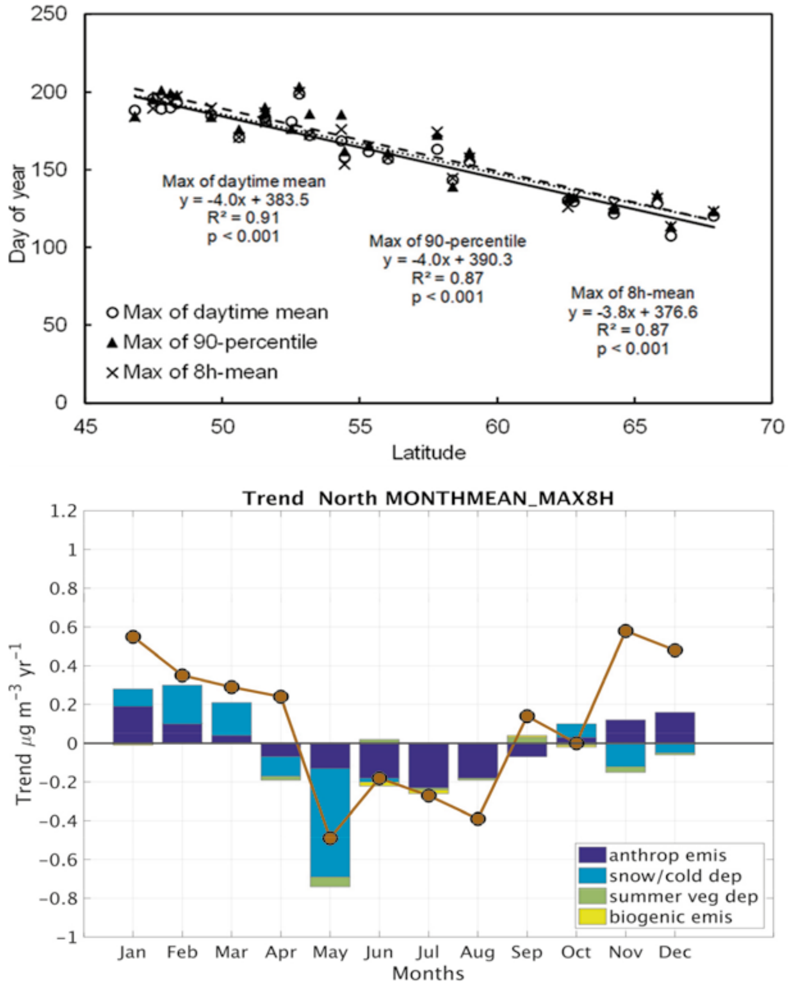


Figure 6.1.
Top: Day of year for the annual maximum ozone concentrations in relation to latitude, based on hourly ozone data from 25 EMEP monitoring sites north of the Alps during the period 1990-2015. Modified from Klingberg et al., 2019.
Bottom: Trends in the seasonal variation in monthly mean of daily maximum 8 hour mean ozone concentrations over the period 1994–2009 in the northern Sweden (Norrland). The trend is included as brown circles. The contribution to the trend is shown as bars for each month, due to changed emissions from Europe (anthrop emis; dark blue); changes in snowcover/cold weather (snow/cold dep, bright blue), trend in vegetation uptake not related to snow and cold (summer veg dep; green) and biogenic emissions (biogenic emis, yellow). Andersson et al., 2020.

In combination, the conditions and changes described above mean that the risk of vegetation damage due to ozone in northern Sweden could potentially increase in the future. To evaluate these risks, a network of scientists from Sweden, Norway and Finland was formed and convened three times during SCAC's project period to exchange experiences and ongoing research results. The overall conclusions from these discussions were that high-altitude vegetation in northern Fennoscandia probably, according to current knowledge, does not run a greater risk of ozone damage compared to vegetation in more southern parts of Fennoscandia. This is due to a near ground growth pattern, in combination with lower ozone levels close to the ground, relatively slow growth rates of these vegetation types and a relatively small leaf area that can absorb ozone in relation to total leaf biomass. This conclusion is valid under the condition that ozone levels in the north do not increase significantly due to human activities, such as increasing emissions of ozone precursor substances from shipping around the Arctic (Karlsson et al., 2020a).

Carbon stocks in Swedish forests increase annually at a rate that corresponds to over half of the CO_2 emissions from all other sectors in Sweden. This is mainly because the annual growth of all Sweden's forests exceeds the annual harvest. A higher growth rate at a constant harvesting rate would mean that carbon stocks could increase even further. Experimental, multi-year studies have shown that ozone can reduce growth rates 4-6% in young trees. It is important to verify that this also applies to adult trees in forest stands.

Annual forest stem growth was calculated based on sampling of tree-rings at 17 different sites with Norway spruce forests in the southern half of Sweden for 23 years, 1990 - 2013. These results were combined with annual values on ozone exposure, nitrogen deposition, air temperatures, number of days with drought and the timing for the start of the growing season. The difficulty with this type of analysis lies in the fact that all these variables vary simultaneously. To solve this, we used a Multiple Linear Regression methodology. The results showed that it was only the negative effect of the number of days of drought that had a fully statistically significant negative effect on growth. There were indications of a positive effect of air temperature and nitrogen deposition. The statistical model indicated a slight negative impact of ozone on growth, but it was far from statistically significant. One conclusion is that in order to establish the effect of ozone on the growth of adult trees in forest populations, a much larger survey material is required, with data from many more measurement sites than was available in this study. On the other hand, it is likely that it would be possible to statistically prove a positive impact of a high nitrogen deposition on the growth of spruce forests in southern Sweden, with a reasonable increase in the number of measurement sites. In a similar study at the European level, with contributions from SCAC scientists, a positive impact of nitrogen deposition on forest stem growth was demonstrated up to an optimum value, above which the impacts of nitrogen deposition became negative (Etzold et al., 2020). Improved methods for calculating the explanatory variables, e.g. that the ozone risk assessment should be based on the amount of ozone that is taken up by the leaves and that the nitrogen deposition also should include the dry deposition, could also contribute to establish the impacts of different explanatory variables with statistical significance.

6.5 Highlights from the research - nitrogen

- Work on developing national nitrogen budgets (NNB) is ongoing within the member countries of the LRTAP Convention. Within the SCAC program, mapping of the Atmosphere pool has been carried out. Thus, four out of eight NNB constituents are completed or almost completed.
- In the atmospheric part, Swedish emissions of reactive nitrogen (Nr), deposition data, contributions from import and export through long-range transport have been compiled for 2015. The nitrogen deposited over Sweden (160 thousand tonnes, kt) in 2015 originated mainly from other countries (139 kt), while three quarters of the Swedish nitrogen emissions (49 kt of the total emissions of 70 kt) were transported to other countries.
- The annual Nr turnover in the atmosphere above Sweden is about 210 kt Nr, with inputs (import + Swedish emissions) of 209 kt and output of 213 kt (total deposition + export). The fact that the budget is balanced within 1% should be seen as well within the margin of uncertainty for the individual budget items.
- As a second part of the nitrogen part of SCAC, we have collected information on which nitrogen fertilization experiments have been carried out in Swedish forest ecosystems, compiled information on where, when and how the experiments were conducted. Due to the limited number of experiments, it is difficult to draw conclusions on impacts on biodiversity from existing experiments.
- A long-term fertilization experiment in Gårdsjön involves repeated vegetation surveys. The results indicate high stability in the composition of vegetation species with relatively modest and slow changes on decadal time scale. The experiment has been ongoing since 1991, with addition of 40 kg N per ha and year.

6.6 Contribution to development of regulations

We have participated in the annual meetings of the Task Force for Measurement and Modelling (TFMM) under UNECE CLRTAP , contributing with knowledge and presenting results from the SCAC research. Furthermore, under the umbrella of TFMM we have engaged in EuroDelta trends (EDTRENDS). This is a multi-model experiment of air quality hindcasts, designed to facilitate a better understanding of the evolution of the evolution of air pollution and its drivers over the period 1990-2010 in Europe. This international collaboration has resulted in 6 research papers (Colette et al., 2017; Vivanco et al., 2018; Otero et al., 2018; Theobald et al., 2019; Ciarelli et al., 2019a; Ciarelli et al., 2019b), improved understanding of major uncertainties (e.g. condensable organics and emissions of organics) and development of chemistry transport models, such as the Swedish MATCH model (a member of the Copernicus

Atmospheric Monitoring Services, CAMS, providing forecasts and analysis of air pollution operationally, http:// https://atmosphere.copernicus.eu/; Marécal et al., 2015), the MATCH-Sweden system (providing national measurement and model fusion products of total atmospheric nitrogen and ozone deposition, operationally; Andersson et al., 2017; Andersson et al., 2018), and the European community model, EMEP. The method of the MATCH Sweden system, using measurement model fusion of nitrogen and ozone deposition (used in the NNB described here), has been identified internationally as state-of-the-art in a number of WMO meetings (e.g. WMO, 2017; WMO, 2020), and the work was presented in these meetings. A representative of the MATCH Sweden system (Camilla Andersson) is now in the WMO steering group for measurement model fusion of Global Total Atmospheric Deposition (MMF-GTAD). Progress and results from constructing the atmospheric part of the Swedish NNB were presented at the Task Force on Reactive Nitrogen (TFRN) Workshop on integrated sustainable nitrogen management organized back to back with TFRN annual meeting (September 30 – October 2 2019, Brussels). Results from the N-addition experiments were presented at annual meetings of Joint Expert Group on Dynamic Modeling in April 2018 and in October in 2019 and contributed to process understanding and model development described in 4 research papers (Moldan et al., 2018; Cheng et al., 2019, Veerrman et al., 2020 and Tahovská et al., 2020).

6.7 Results - nitrogen

6.7.1 Sweden's national nitrogen budget

Work on developing national nitrogen budgets (NNB) is ongoing within the member countries of the Air Convention. A national nitrogen budget covers all important nitrogen pools in the country where the nitrogen in all its reactive forms is to be included, i.e. nitrogen in all forms except N_2. The purpose is to make the size of nitrogen flows more visible in order to prioritize measures to reduce emissions both nationally and internationally. Within the Air Convention, the national nitrogen budget is divided into eight main parts (Energy and Fuels, Materials & products, Agriculture, Forests and semi-natural vegetation, Waste, Humans and settlements, Atmosphere and Hydrosphere). IVL, on behalf of the Swedish Environmental Protection Agency, has compiled the section Agriculture (Stadmark et al. 2019). There is also a parallel work on the Forests and semi-natural vegetation pool in a project funded by the Swedish Environmental Protection Agency and also a compilation of the Hydrosphere pool, which is almost completed. Within the SCAC program, work with the Atmosphere pool has been carried out in collaboration between SMHI and IVL (Moldan et al., 2020). The work on compiling the complete NNB for Sweden is ongoing and the impact of this work on decision making and on the work of LRTAP will be possible to evaluate only when the work is completed. However one specific lesson learned based on Swedish experience is that while the task of compiling whole NNB for a country requires substantial concentration of resources which may be problematic to find, the eight major parts have their specific relevance to different funding agencies, such as the atmospheric part has relevance for SCAC 2 program. A stepwise approach might be an efficient way to complete the whole task and this message was also communicated to TFRN on its 2019 annual meeting.

In the atmospheric section, Swedish emissions of Nr, deposition data, contributions from import and exports through long-distance transport have been compiled for 2015. In addition to these four main flows of Nr to and from the atmosphere, production of Nr from lightning has also been quantified. The nitrogen deposited over Sweden (160 kt) in 2015 came mainly from other countries (139 kt). About three-quarters of the Swedish emissions of 70 kt were transported to other countries (Figure 7.1). The main sources of emissions in 2015 were agriculture (40.6 kt) and energy conversion and combustion processes, for example in the form of transport (20.9 kt). The annual Nr turnover in the atmosphere above Sweden is about 210 kt Nr, with inputs of 209 kt and output of 213 kt. The fact that the budget is balanced within 1% should be seen as well within the margin of uncertainty for the individual budget items.

The budget for 2015 has also been set in relation to annual nitrogen deposition since 1983, estimated with the MATCH Sweden system (nitrogen reanalysis; Andersson et al. 2018), see Figure 7.2. There has been a reduction of total reactive nitrogen deposition in Sweden by 30% from the first 10 years to the last 10 years of the period. The decrease is statistically significant. The ecosystems that receive the most nitrogen during 2015 are spruce and pine forest (27 and 24%, respectively), sea and lakes (21%), and agricultural land (11%).

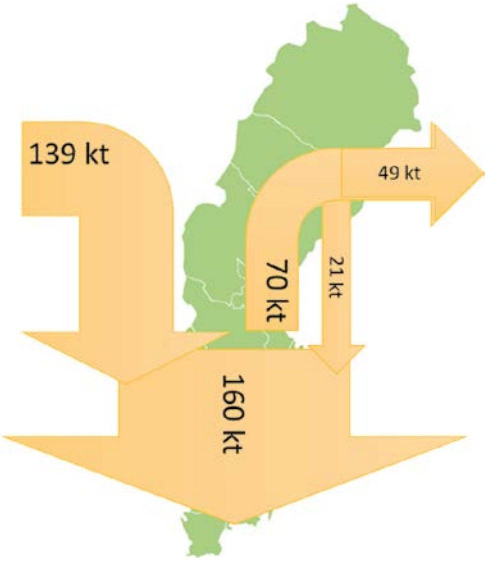


Figure 6.2. The main Nr flows to and from the atmospheric part of the Swedish national nitrogen budget in the year 2015. The inputs are the imported air pollution (139 kt) and Nr emissions within Sweden (70 kt). The outputs are deposition (160 kt of which 21 kt originates from Swedish emissions) and exported Swedish national emissions (49 kt).

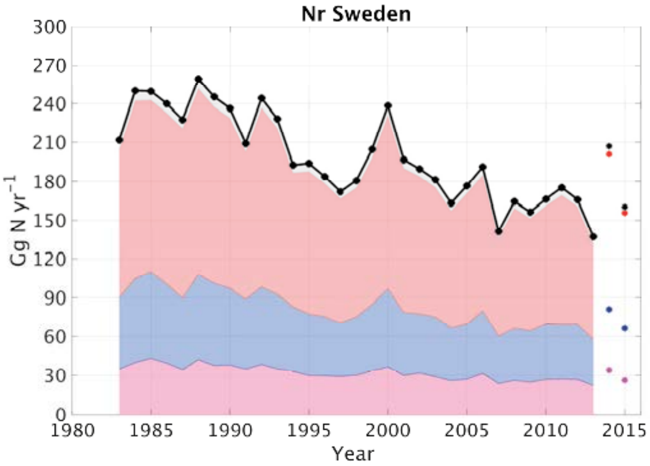


Figure 6.3. Total reactive nitrogen deposition to Sweden in the period 1983-2015 and deposition contributions to forests (red), water surfaces (blue) and agricultural land (magenta). Accumulated deposition by contributions (surfaces and circles) and total (black). Lines/surfaces: MATCH Sweden system reanalysis (1983-2013). Circles: operational MATCH Sweden system estimates (2014 and 2015).

With the compilation of the atmospheric component of NNB, four out of eight constituents of NNB are now finalised. Agriculture supplies the largest amounts of nitrogen in the form of inorganic nitrogen for fertilizers (190 kt) and in feed for the animals (59 kt). Nitrogen fixation (34 kt) and atmospheric fallout (18 kt) also contribute nitrogen to the agricultural pool. The nitrogen that leaves the agricultural pool does so mainly in the form of crops (135 kt), as leakage to the hydrosphere (53 kt) or emission to the atmosphere (40 kt) and in the form of biomass, which includes meat and milk (36 kt).

In the hydrosphere part, leaching from agriculture (53 kt), forestry (48 kt) and other land (e.g. wetland) (20 kt) and atmospheric deposition to surface waters and sea (33 kt) make up the largest nitrogen flows, while drainage to the sea (115 kt, where about 18 kt is denitrified in the coastal zone), and retention of nitrogen in inland water (35 kt, mainly through denitrification) is what constitutes the nitrogen flows from the hydrosphere.

In the section on forest and semi-natural ecosystems, the final results are under construction (with a later deadline). The results show that the extraction of nitrogen from the forest in the form of raw material withdrawals and emissions from the soil and deposits constitute the large outflows and inflows of Nr.

6.7.2 Nitrogen fertilisation experiments

Nitrogen supply via precipitation or fertilization can affect the biodiversity of ecosystems. In the case of high nitrogen additions, both nutritional status and acidity in the soil are affected and favour the species that are most competitive under the given conditions. In SCAC, we have reviewed which nitrogen fertilization experiments that have been carried out in the Swedish forest environment ecosystems and compiled information on where, when and how the experiments were conducted. The overall goal of these experiments was to investigate forest growth, as forest raw material production is an important ecosystem service in Sweden. For this reason, the impact on vegetation composition has only been studied in a few experiments and the knowledge of changes in the biodiversity in these production forests is therefore limited. From a conservation perspective, studies of vegetation changes over a long period of time in other ecosystems than forests are important for understanding the impact of nitrogen deposition. Most European ecosystems have been affected by human / anthropogenic supply of nitrogen for a long time and have therefore already changed. Long-term effects of nitrogen supply are therefore difficult to investigate in (new) field experiments.

This challenge can to some extent be addressed by modelling using data from areas with similar natural conditions, but with higher or lower anthropogenic nitrogen supply. Through biodiversity modelling, various future scenarios can be investigated and changes in vegetation composition linked to altered nitrogen deposition studied. Work on these issues will continue in new projects. SMHI collaborates with Lund’s LPJ-GUESS model group to look at future scenarios for ecosystems based on future climate and air environment in northern Scandinavia within the BioDiv-Support project (https://www.smhi.se/forskning/forskningsomraden/luftmiljo/biodiv-support -1.145908). As of January 2020, a new program centre, Centre for Dynamic modelling (CDM), has been launched within the Air Convention with the mandate to coordinate biodiversity modelling within the Convention. In both of these activities, the results from the SCAC compilation will be used further.

7 How to choose the right measures to ensure co-benefits between climate and air pollution solutions?

Emissions of air pollutants and greenhouse gases often stem from the same sources: combustion of fuel and agricultural activities. Further, the options available to reduce emissions often have effects on several pollutants and greenhouse gases. And once emitted air pollutants affect not only the environment but also climate change, and greenhouse gas emissions affect not only the climate but also ecosystems' sensitivity to air pollution. There are thus direct physical and economic links between air pollution and climate change that can be considered when analysing options to reduce emissions. For an option aimed at reducing impacts of climate change or air pollution, the links can be of mutual benefits (co-beneficial) or antagonistic (causing trade-offs). In SCAC we have studied ways to improve existing decision support models with respect to how these aspects are considered, as well as studied which options that are co-beneficial and which induce trade-offs.

7.1 Key messages

The research in SCAC has focused both on testing and developing the existing decision support models Greenhouse Gas - Air Pollution Interactions and Synergies (GAINS) developed by the International Institute for Applied Systems Analysis (IIASA) and Alpha RiskPoll (ARP) developed by EMRC (section 7.4) as well as on analysing the potential for reducing emissions further and ensure co-benefits between air pollution and climate change. Based on our and others research a couple of key messages can be suggested.

Current air pollution decision support models only present economically rational trade-offs between known emission control costs and benefits, not what will happen as response to a policy initiative.

Many models are perceived as 'black boxes' for the receiver of the model results, and given the political importance of economic rationality, this opaqueness becomes especially problematic in economic decision support modelling. With SCAC we had the chance to reflect and contemplate on the methodological validity of these models. The scientific and moral controversy around economic rationality in general (and cost-benefit analysis in particular) is established by now (Frank 2007, Schlefer 2012, Sen 1977) and new research provides more reasons for scepticism (Arthur 2014, Neuman-Lee & UTROG 2016, Thaler 2017). However, this criticism needs to be balanced against the desire to base decisions on fact-based and rational approaches, the functionality of political negotiations, and the lack of competitive alternatives. So even though it can be recognised that there is much room for improvement, one should still consider the current decision support models as fit for purpose: they can be used to identify the right measures to ensure co-benefits between air pollution and climate change. But the receiver must always remember that the model results are idealised solutions based on current knowledge. They do not claim to make forecasts, are made to analyse small perturbations in the economic system and doesn't consider the emergence of new game-changing technologies.

Alternative rationales need to be presented by decision support models

Although the decision support models can be defended on the balance, one key issue of importance for future decision support is that the economic rationality is complemented by other forms of rationality. As an example, in parallel to presenting results from economic models it is important to present results that shows which emission levels in Europe that would ensure achievement of current EU environmental ambition levels: "*levels of air quality that do not give rise to significant negative impacts on, and risks to human health and environment.*" (European Commission 2014).

The use of climate metrics as indicators of climate effects is solid enough to use in air pollution decision support modelling.

Most decision support models must rely on climate metrics as indicators of climate change effects from emissions to the atmosphere, the most well-known one being global warming potential (GWP). However, earlier research show that it is difficult to come up with an 'one-size-fits-all' indicator, and it has been suggested that the choice of metric to use is a normative choice (Tanaka et al. 2014). Although this is certainly true when using metrics to prioritize between long-lived or short-lived emissions, our research shows that it is not important when prioritizing between air pollutants with effects on climate change (Åström & Johansson 2019). So even though it might be confusing to see various metrics used in calculations of climate effects of air pollution emissions (such as global temperature potential with a 10-year target (GTP10) or GWP with a 100-year time horizon), this variance will not significantly affect which options that are cost-effective means to reduce emissions. The important caveats are if the options also affect NO_x or CO_2 emissions. Overall, the identification of a cost-effective air pollution control option to reduce climate change is not affected by the climate metric used in the analysis.

Efficiency improvements, non-combustion energy sources and behavioural changes all ensure co-benefits between climate change and air pollution.

Over the last 20 years, much research has been done on co-benefits and trade-offs between air pollution and climate change (for a review see Karlsson et al. 2020). By now there are a couple of general themes that can be distilled out. There are a couple of risks for trade-offs. First and foremost, the use of solid biofuels for electricity and heating can decrease CO_2 emissions but is at risk of increasing emissions of some air pollutants. Secondly, the use of flexible mechanisms such as the EU emissions trading system is at risk of geographically placing emission reductions in areas where air quality benefits are lower than what could have been achieved if considering also effects on air quality. However, the general lesson from the research show that also efficiency improvements (including electrification of mobility) and the use of solar and wind power have ample potential for co-benefits between climate change and air pollution. And in addition, a recent SCAC study shows that behavioural changes, even incremental ones, both have significant effects on emissions of air pollutants and imply co-benefits between climate change and air pollution (Åström 2019a).

7.2 How can these SCAC results aid development of policy?

Within SCAC, IIASA and IVL have continued development of the GAINS model control cost optimization routine so that it now, in a Scandinavian setting, can find cost-minimizing ways to reduce effects on human health, environment and climate from emissions of SLCFs, allow for consideration of uncertainty in control cost data, enables joint cost-effectiveness analysis of emission reductions at sea and at land, and can check for effect on CO_2 emissions of implementing air pollution control technologies. Most of these developments have not yet been published in scientific journals but are documented in a forthcoming model report (Åström et al. forthcoming). Further, SCAC research has contributed to monetization of damage costs for three health effects attributable to poor air quality (Figure 7.3) and are now discussing with EMRC the possibility to include these into the ARP model. These developments are relevant for policy makers since they enable more robust analysis of emission control and 'no-regret' implementation of air pollution control, analysis of whether it is cost-effective to reduce emissions at land or at sea, as well as enhance the endpoints included in future air pollution cost-benefit analysis (CBA).

SCAC has over the years also analysed options for reducing emissions from road transport, shipping, household wood combustion and agriculture, as well as dedicated focus to behavioural change measures. These analyses provide quantitative estimates of the future potential for emission reduction – in some cases also estimates of costs of the options – and are useful as decision support during policy preparation.

On a wider scale, given future policy discussions to come in Europe, SCAC has added to the body of knowledge on how well the tools, models and methodologies used today are fit for purpose. Such review is important to ensure continuous model improvements and to ensure that the best available fact-based and rational approach is used for science-based policy support.

7.3 Results

The research presented in this chapter can be grouped in two parts. The first group contains results from studies of the methodology and tools used in air pollution decision support analysis. The second group contains research on options to reduce emissions. The driver of much of the research has been the fact that CBA accompanying policy proposals now is used to derive the proposal, rather than to check the economic soundness of a proposal.

7.3.1 Methodology and tools for decision support

Currently in the CBA used to support EU air pollution policy, the CBA calculate the emission level where the costs of reducing one extra unit of emission is equal to the benefit of reducing one extra unit of emission. This emission level is then by economists considered a cost-efficient emission level, and the emission level can then be used as basis for a policy proposal. However, the CBA results are dependent on the amplitude, shape, and curvature of the cost and benefit curves, all features very dependent on choice of methods and data to include.

In Åström (2019b) it is re-affirmed that the methodological foundation of CBA is criticised, and that the body of criticism is growing. But it is also found that since environmental policies depend on support also from arenas outside science it cannot be stated that the CBA-shortcomings impairs the air pollution policy process, but it can be stated that the CBA approach is fit for purpose, as long as one bears in mind important methodological shortcomings and that the CBA approach isn't the only useful approach. There are arguments for inter alia complementing CBA with analyses based on non-economic decision rationales.

On a more model technical-level, Åström and Johansson (2019) find that the choice of climate metric does little to alter which air pollution control option that is most cost-effective from a climate change perspective (Figure 7.1), whilst Åström et al. (2018a) find that the choice between short-term or long-term thinking (i.e. corporate or social planner[1]) has an irregular but sometimes significant effect on which emission control options that are to be considered cost-effective, with corresponding risk for using cost-inefficient strategies to reach air pollution targets (Figure 7.2).

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[1] In the modelling done, the corporate perspective is characterized by a 10% investment rate and an up to 10-year lifetime of investment, whilst the social planner perspective is characterized by a 4% investment rate and technical lifetime of investment

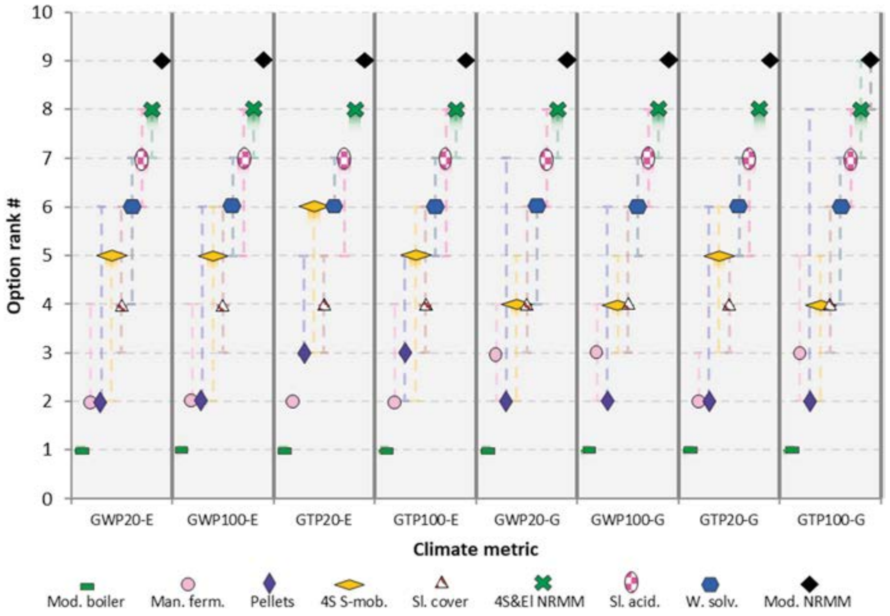

Figure 7.1: The cost-effective rank of 9 options (bottom legend) to reduce air pollution with significant climate effect as a function of which climate metric that is used (GWP or GTP with 20 or 100 year horizons for European average (E) or Global average emissions (G). Copied from Åström and Johansson (2019).

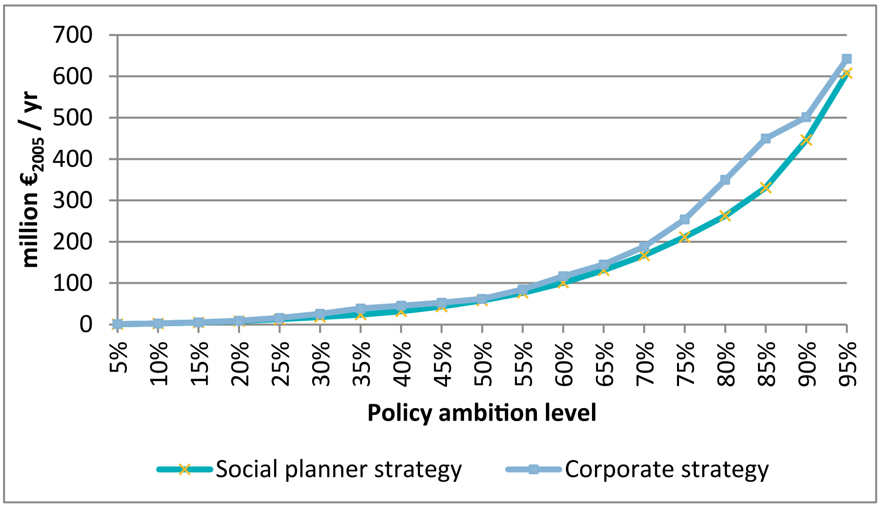

Figure 7.2: The social-planner cost curves over the range of technically available policy ambition levels for the Nordic countries in 2030 if technologies are chosen with a corporate perspective or with a social-planner perspective. At 85% policy ambition level the cost penalty for society of choosing technologies with a corporate perspective corresponds to ~120 million 2005 per year (indicated by the gap between the social planner strategy cost curve and corporate strategy cost curve at 85% policy ambition level).

With respect to the benefit side, Kriit & Åström (under review) suggest that economic costs of one incidence of the air pollution-related health outcomes stroke, myocardial infarction and preterm birth are 175–1140, 16–38 and 10–45 thousand €$_{2016}$ respectively (Figure 7.3). The value of reducing the frequency of these outcomes through improved air quality in Sweden is at least 11–73% of the values considered in comparable CBA:s such as ARP (when comparing with mortality valued per life-year lost).

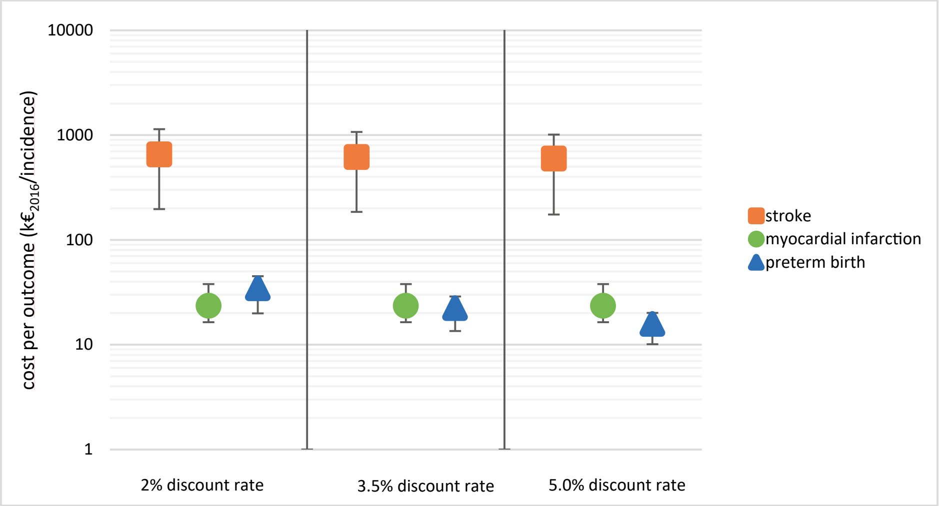

Figure7 3 Swedish socio-economic damage costs of one incidence of stroke, myocardial infarction or preterm birth induced by air pollution (Kriit & Åström, under review)

7.3.2 Options to reduce emissions

When studying options to reduce emissions, Hellsten (2017) find that the most cost-effective ammonia control measures in Sweden are low nitrogen feed, low ammonia application of manure, and low emission manure storage. Measures to reduce housing emissions, e.g. designing the stable to reduce the surface and time manure is exposed to air, are also rather cost-effective, particularly for new stables. Hellsten also discuss the policy challenge involved in achieving reduced consumption of meat and dairy products, including challenges related to import/export of food items. This latter option would also have significant co-benefits with climate change. Hellsten et al. (2019), when taking a Nordic perspective, push the need to ensure that the nitrogen application rate on soil and its timing should be in accordance with the crop need and carrying capacity of environmental recipients.

Emissions from international shipping is another source of poor air quality studied within SCAC. Åström et al. (2018b) studied the policy solution to introduce a nitrogen emission control area in the Baltic and North seas with a CBA and conclude that the NECAs for the Baltic and North Seas can be justified using CBA under all but extreme assumptions (Figure 7.4). Of relevance for co-benefits between climate change and air pollution they also find that conforming to the NECA regulations by using Liquefied Natural Gas (LNG) propulsion engines could give the highest net benefits but also the largest variation. The variations are mainly due to uncertainties in the valuation of avoided fatalities and climate impacts, where methane slip from the LNG engines is an important technology failure that needs to be avoided.

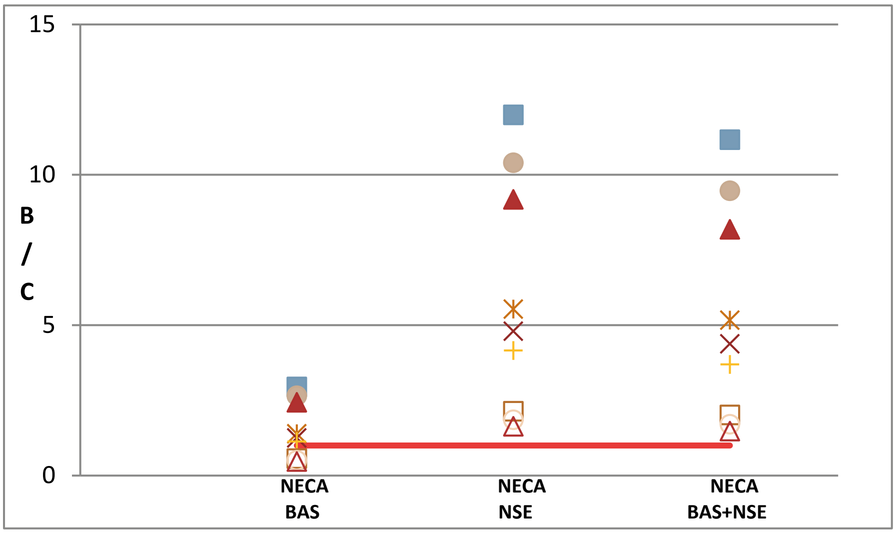

Figure7.4 Benefit/Cost-ratios for NECA in the Baltic Sea (BAS), North Sea (NSE) or both sea regions given uncertainty over costs and benefits. The red line indicates a B/C over 1, i.e. a socio-economic beneficial solution. A NECA in the North Sea has the highest net benefit.

For road transport, Åström (2018c) confirms that the current Swedish climate strategy (SOU 2016) for the most part will have co-beneficial effects with air pollution. The climate strategy can help Sweden reach a bit more than half of the 2030 Swedish NO_x obligations under the National Emissions Ceiling Directive, which means that continued implementation of dedicated air pollution control (such as end-of-pipe) should be necessary. Also emissions of PM2.5 and NMVOC would be reduced through the climate strategy. Åström et al. (2016), although not directly a SCAC research activity further stress the need to contemplate scrapping options to reduce future emission from road transport. Both Åström et al. (2016) and Åström (2018c) reconfirms the co-beneficial features of electrified road transport.

The last sector studied is household wood combustion. Although not a SCAC study, the results by Kindbom et al. (2018) suggest that there is a significant technical potential to reduce the adverse health effects and, to some extent, the climate impact from future residential biomass combustion in Denmark, Finland and Sweden by reducing emissions of air pollutants. The amounts of wood used, penetration of modern technology in residential biomass combustion and the user behaviour in managing the combustion process all have significant impacts on the emission levels in the three Nordic countries. Again Åström et al. (2016) show the potential importance of scrapping old technology to achieve significant future emission reductions.

Finally, Åström (2019a), when studying potential effects on emissions from implementation of 10 documented behavioural change options to reduce emissions, finds that the behavioural changes affecting emissions of NO_x could contribute with some 12-24% of the required additional Swedish emission reductions in 2030. As mentioned, these measures are multipollutant and co-beneficial in their nature. If all the 10 studied measures would be implemented emissions of CO_2 could be reduced by approximately 2-4 Mtonne in 2030 (the nature of the measures impede separation between biogenic and fossil CO_2). Even though uncertainties are large, much due to lack of theory and data, the best estimate is that there still in 2030 will be a potential to substantially reduce air pollution and greenhouse gas emissions in Sweden through behavioural change.

7.4 Main methods

Given the multiple facets of air quality problems, integrated analyses are used to ensure that any policy impact assessment reasonably estimates the multiple effects, geographical differences, and varying socio-economic development of relevance for air pollution policy. Further, scenario analysis is used since structural changes in the economy, changes in fuel use, and changes in industrial production all affect future emission levels. To meet these demands, integrated assessment models (IAMs) such as UKIAM (Oxley et al. 2003), MERLIN (Reis et al. 2004), RAINS (Amann et al. 2004), and GAINS (Amann et al. 2011, Kiesewetter et al. 2014, 2015) have been developed. In SCAC we have adapted a Fenno-Scandinavian version of the GAINS model, originally developed by IIASA. Basically, the GAINS model is used to analyse which control options that should be implemented to cost-effectively control emissions from European countries and how large the control costs would be for a given policy target. The options available for consideration are mainly different end-of-pipe options. The GAINS model considers: that several pollutants contribute to one or several environmental problems and climate change; that ecosystem sensitivities vary between countries; that emission dispersion and mixing in the atmosphere follow certain meteorological conditions, and that the economic structure of a country affects the ability and cost of emission reduction. Through the focus on socio-economic costs, the models can also identify in which sectors options should be implemented to provide lowest costs for the entire economy.

Evaluation of policy proposals via appraisal and comparison of costs and benefits, CBA, has become more and more important for air pollution policy. There are two main versions of CBA applied for air pollution policy analysis, one version based on optimization and one version based on scenario comparisons. Within SCAC we have mainly discussed and used the ARP model (Holland et al. 2013), which is mainly developed for scenario comparisons, but can with some tweaks be used to give input to the benefit curve in an optimization.

8 References

For additional reports and publications from the SCAC program, please visit www.scac.se

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Final report second phase

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