Project no. 282688

ECLIPSE

Evaluating the **Cl**imate and Air Quality **I**m**p**acts of **S**hort-Liv**e**d Pollutants

Collaborative Project

Work programme:	Climate forcing of non UNFCCC gases, aerosols and black carbon
Activity code:	ENV.2011.1.1.2-2
Coordinator:	Andreas Stohl, NILU - Norsk institutt for luftforskning

Start date of project:	November 1st, 2011
Duration:	36 months

Deliverable: D7.1
Documentation on the extensions of the GAINS model to include short-lived climate forcers (R)

Due date of deliverable: project month 13
Actual submission date: project month 18

Organisation name of lead contractor for this deliverable: IIASA
Scientist responsible for this deliverable: F. Wagner

Revision [v1]

Project co-funded by the European Commission within the Seventh Framework Programme (2007-2013)		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Documentation on the extensions of the GAINS model to include short-lived climate forcers

F. Wagner, C. Heyes, Z. Klimont, M. Amann, W. Schoepp, G. Kiesewetter
International Institute for Applied Systems Analyss
(IIASA), Schlossplatz 1, 2361 Laxenburg, Austria

SUMMARY

The work on this deliverable is part of the task T7.1 (Implementation of new information on emission inventories for short-lived substances, climate metrics and corresponding source-receptor relationships into GAINS).

The report describes the new elements in the GAINS model that address short-lived climate forcers, specifically adaptation of the model to use newly developed metrics within other ECLIPSE tasks and implementation of the BC and OC source receptor relationship for Europe. Beyond that, brief account of the major changes in the emission model since UNEP work is also provided.

The GAINS model went through a number of developments since the UNEP study was completed in 2011. It does not consider only new emission scenarios (ECLIPSE provided a specific deliverable D1.1 on that topic) but changes to the structure of the model or characterization of some sectors. From the perspective of the short-lived climate pollutants (SLCP) key changes include: extension of the brick sector to improve representation of brick making technologies across the world, distinction and new estimate of fuel use and emissions from diesel generators as well as kerosene wick lamps, specific calculation of OM beyond already calculated BC and OC primary emissions, updates to methane estimates and projections.

Inclusion of the effect of SLCPs allows us to analyse synergies and trade-offs between health effects from $PM_{2.5}$ exposure and primary particles with a warming effect (e.g. black carbon), as well as precursors of particles with a cooling effect (e.g. SO_2). In this work changes in radiative forcing are calculated for the new steady-state condition of the atmosphere following a sustained change in emissions, calculated globally and for an extended region covering Europe. Source-receptor (SR) calculations have been performed to assess the effect of emissions from individual EMEP countries on global aerosol loading. In each SR run one of the following species was reduced by 15% in one country: SO_2, NH_3, VOC, NO_X, BC and primary organic carbon (POC). Normalised radiative forcing (NRF) is defined as the radiative forcing (units of W/m^2) divided by the total burden of a species (units of g/m^2), i.e. NRF has units of Watts per gram (W/g). Normalised radiative forcing factors were provided to GAINS by CICERO.

The first set of numbers representing new metrics for SLCPs has been provided by CICERO to IIASA towards the end of 2013. This metrics include GTP and GWP (for 20 and 100 years) values where different regional (Europe, China, Rest of the World) and seasonal (summer, winter) numbers are given. This new and unique metric and its application will be described in detail in a separate deliverable within ECLIPSE.

1 Introduction

The work on this deliverable is part of the task T7.1 (Implementation of new information on emission inventories for short-lived substances, climate metrics and corresponding source-receptor relationships into GAINS name). It contributes to the following objectives of the ECLIPSE project:

- O7.1 – Develop sets of promising measures that result in effective improvements for near-term climate change, long-term climate change and air quality, respectively.
- O7.2 – Identify set of measures that maximize co-benefits between near-term climate change, long-term climate change and air quality, and minimize trade-offs between these objectives.
- O7.5 – Explore various options for addressing short-lived components in global or regional climate policies

This report briefly discusses key updates in the emission calculation component of the GAINS model since the UNEP (UNEP/WMO, 2011) study, gives a detailed account on implementation of the BC and OC transfer coefficients, and finally addresses the extensions needed in the model to accommodate for new metrics developed within the ECLIPSE project. While these new metrics are used in GAINS to identify sets of SLCP mitigation measures, their detailed discussion are subject to other ECLIPSE reports.

2 Emissions and mitigation measures

The GAINS model (Amann et al. 2011) went through a number of developments since the UNEP (UNEP/WMO, 2011) study was completed. It does not consider only new emission scenarios (ECLIPSE provided a specific deliverable D1.1 on that topic) but changes to the structure of the model or characterization of some sectors. From the perspective of the short-lived climate pollutants (SLCP) key changes include:

- Update of brick sector in GAINS where the list of technologies was extended to cover the variety of kilns used across the world; previous version focused on Asia where majority of brick are produced. The purpose of this update is to enable better representation of this sector in several global regions but also respective mitigation potential. For example, GAINS includes now the so called Zig-Zag kilns which offer a promising option in South Asia as well as Marcos (MK) kilns for Mexico and some other Latin American countries.
- The calculation of the particulate matter mass balance in emission factors has been revised leading to a better-defined BC, OC, and OM components. This change has influenced the BC/OC ratios for some sectors and so might have impacts on the outcome of the model when identifying SLCP measures.
- The specific distinction of diesel generators is included in GAINS latest version. This sector has been previously part of the power generation sector without more specific technology description. Current extension should enable identification of potential for mitigation of BC emissions from often poorly operated diesel generators, especially in several South Asian and African countries.
- Mitigation of emissions from flaring in oil and gas industry sector has not been specifically addressed in the UNEP report. More recently, we have reviewed progress inn several countries and used recent industrial information to add such possibility
- A new study (Lam et al, 2012) identified significant source of black carbon which has not been specifically addressed before – kerosene wick lamps. GAINS model did not distinguish emissions from these lamps as a separate category but the fuel

consumption was part of the residential use (typically included under cooking) as there was no emission factors for these lamps. The new study has shown very high emission factors and since there is identifiable mitigation potential (e.g., LED lamps), we have included this in GAINS and expect that this measure will be part of the ‘short list’.

- For methane, we have made use of the latest GAINS assessment (Höglund-Isaksson 2012) which leads to updated emissions and mitigation potential in several sectors

3 Implementation of BC and OC transfer coefficients

3.1 Radiative forcing

Reducing those SLCPs that have a warming effect may offer possibilities to mitigate near term climate change; there has been increasing interest in research on their emissions, distributions and effects. Inclusion of the effect of SLCPs allows us to analyse synergies and trade-offs between health effects from $PM_{2.5}$ exposure and primary particles with a warming effect (e.g. black carbon), as well as precursors of particles with a cooling effect (e.g. SO_2).

In this work changes in radiative forcing are calculated for the new steady-state condition of the atmosphere following a sustained change in emissions, calculated globally and for an extended region covering Europe.

BC is an efficient absorber of solar radiation and contributes to global warming (IPCC 2007). By contrast, sulphate, nitrate and OC aerosols contribute to atmospheric cooling through reflecting solar radiation and modifying cloud properties. Aerosols with optically different properties (and thus different effects on climate) are often emitted from the same sources. Hence the net effect on climate following a reduction of particle emissions from one specific source is ambiguous until at least the relative amounts of BC, OC, and other aerosol emissions from that source are known.

Source-receptor (SR) calculations have been performed to assess the effect of emissions from individual EMEP countries on global aerosol loading. In each SR run one of the following species was reduced by 15% in one country: SO_2, NH_3, VOC, NO_X, BC and primary organic carbon (POC).

Normalised radiative forcing (NRF) is defined as the radiative forcing (units of W/m^2) divided by the total burden of a species (units of g/m^2), i.e. NRF has units of Watts per gram (W/g). Conversely, RF can be calculated by multiplying NRF with burden. Normalised radiative forcing factors were provided to GAINS by CICERO. They were calculated by the global chemical transport model OsloCTM2 for BC, POC, SO_4 and NO_3 components. The forcing due to secondary organic aerosols, however, has not yet been considered. Indirect effects of aerosols, which are associated with significant uncertainties, are excluded and the influence of atmospheric ozone burdens on radiative forcing- related to NO_x and VOC emissions - is also ignored. A comprehensive description of the estimation of the radiative forcing due to the direct aerosol effect, including comparison with multiple aerosol observations, is provided by (Myhre et al. 2009).

Initially, the whole Northern Hemisphere, the EMEP region and the Arctic are being considered as receptor regions. By means of the transfer coefficients it is possible in a straightforward way to estimate the influence of each EMEP country on the RF in these regions (for those aspects of RF included in this assessment) for any particular emissions scenario. Radiative forcing of the short-lived aerosol forcers is calculated - as all other environmental impacts - as linear functions of the relevant pollutants, using matrix source-receptor relationships derived from a set of full EMEP model runs. The relevant precursor emissions for the radiative forcing calculation are SO_2, NO_X, BC and OC. Emissions from all regions in the EMEP domain are used as input to the forcing calculation, contributions from other source regions are absorbed into constants. The relative magnitude of these constants can be significant, owing to the fact that the background contribution can be dominant. The following equation shows how, in the GAINS model, emissions *E* from countries *i* and radiative forcing over receptor region *k* are related:

$$RF_k = \sum_i \sum_p T_{ik}^{RF,p} \cdot E_{i,p} + k_k^{RF}$$

where the *p* are the relevant pollutants. The constant ${k^{RF}}_k$ represents the forcing resulting from emissions from outside the EMEP modelling domain. It is calibrated to ensure consistency between the EMEP model and the GAINS model for the base scenario from which the transfer matrices are derived.

This initial implementation of source-receptor relationships for instantaneous radiative forcing within GAINS takes into account the emissions of BC, OC, SO_2, and NO_x, as precursors but neglects the effects on sulphate and nitrate aerosol concentrations caused by changes in NH_3 emissions. The EMEP global model predicts that reductions in NH_3 emissions will result in an increased column burden of sulphate aerosol but the size of the overall effect over Europe is small (<5%) in comparison with the change - in the opposite direction - caused by corresponding reductions in SO_2 emissions.

Reductions in NH_3 emissions have a relatively more significant impact in decreasing nitrate aerosol column concentrations, broadly comparable to that of NO_x emission changes in the EMEP model results. However, the contribution of the nitrate aerosol to the calculated radiative forcing is minor compared to that from sulphate aerosol, and, indeed, BC. In these circumstances, excluding ammonia from this preliminary implementation is unlikely to have a major influence on the outcome. This approach is, in addition, consistent with that adopted within the current version of GAINS to estimate the deposition of acidifying and eutrophying species, where ‘cross-terms’, for example the change in deposition of oxidised nitrogen as a result of changes in NH_3 emissions, are also neglected.

The above transfer matrices *T* vary by source regions and pollutant. Figure 1 shows the values of the transfer matrices for SO_2 and NO_X, the top left panel for all EMEP countries, the other panels provide more detail for the three clusters identified in the top left panel.

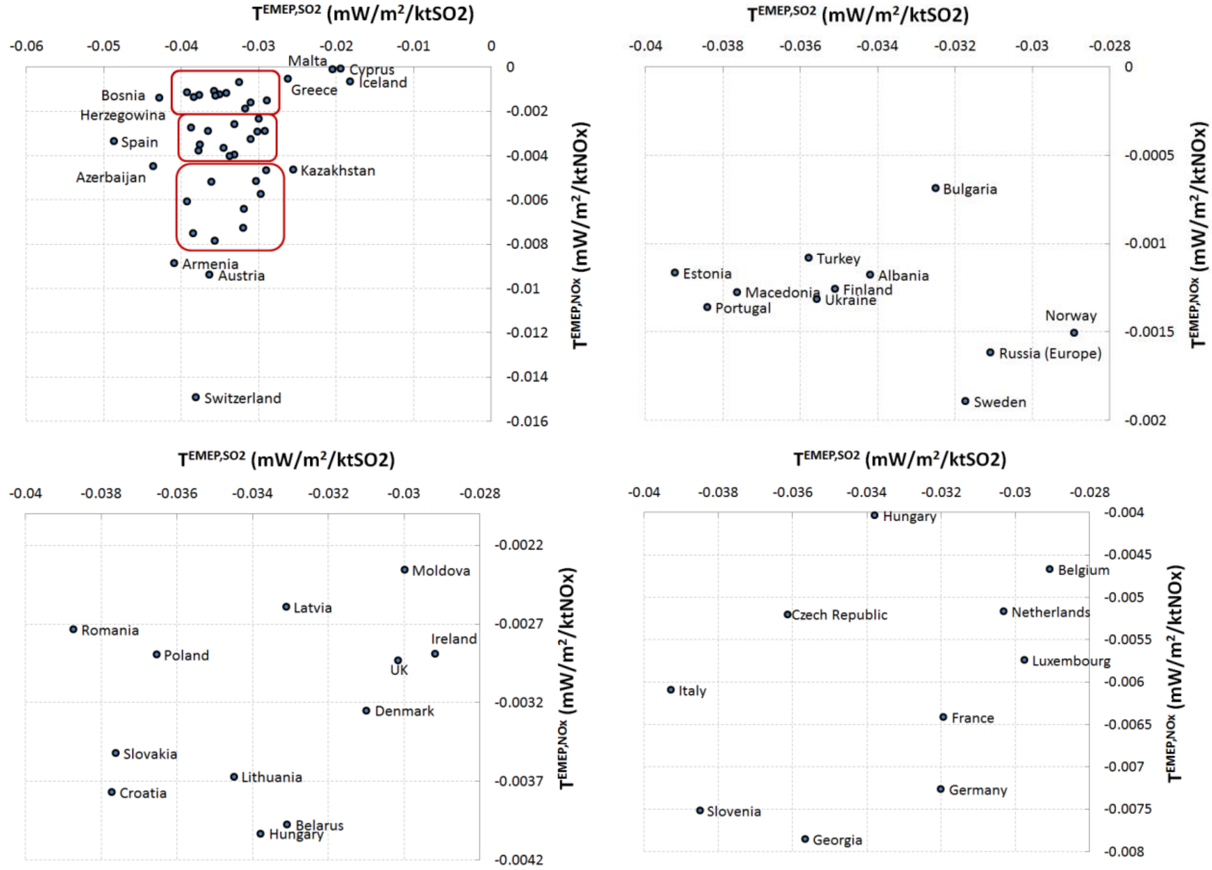
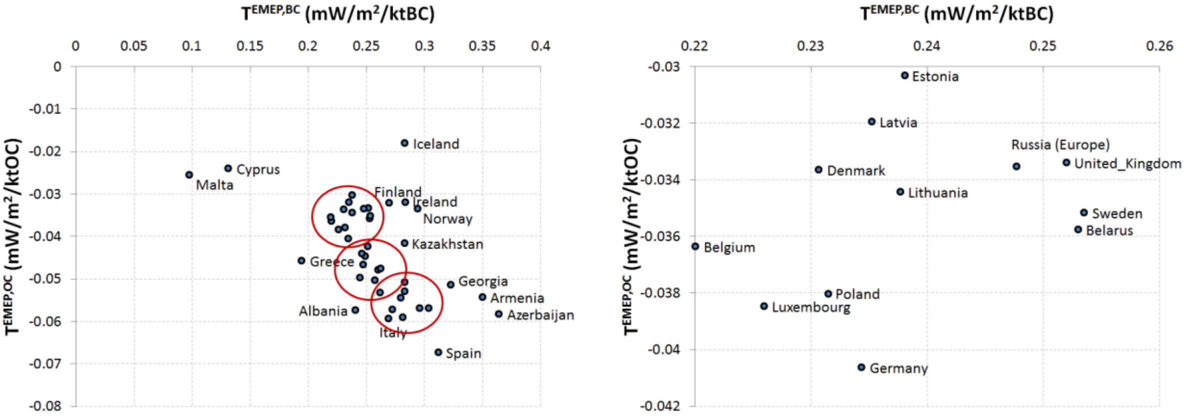


Figure 1 Size distribution and relation between source-receptor matrices *T* for SO_2 and NO_x (in NO_3 calculation) from European countries to the EMEP region. Top left: all countries. Other panels: countries falling into one of the three clusters identified in the top left panel.

Similarly, Figure 2 shows the values of the transfer matrices for BC and OC, the top left panel for all EMEP countries, the other panels provide more detail for the three clusters identified in the top left panel.



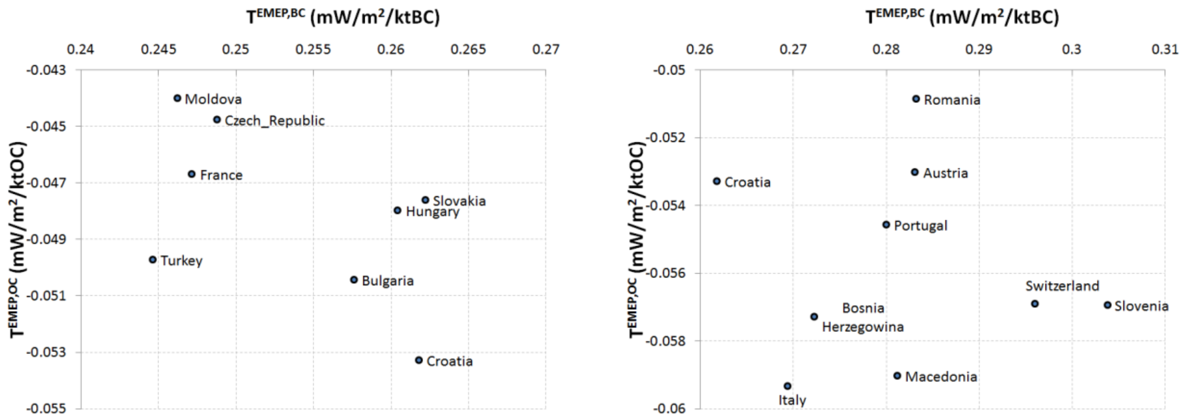


Figure 2 Size distribution and relation between source-receptor matrices *T* for BC and OC from European countries to the EMEP region. Top left: all countries. Other panels: countries falling into one of the three clusters identified in the top left panel.

In absolute terms, the BC coefficients are half an order of magnitude larger than those of OC and SO_2, while the NO_x coefficients are again one order of magnitude smaller. In general, however, the potential for reducing these pollutants also differs significantly. For example, we estimate that for the UNECE or EU27 region as a whole the absolute potential for reducing SO_2 is between 10 and 25 times larger than the potential for reducing BC, and 5 to 10 times larger than that of OC, while it has the same order of magnitude as the potential for reducing NO_x. It is understood that measures that target $PM_{2.5}$ emissions also reduce the subspecies BC and OC, and vice versa. However, the extent of the co-control depends on the exact technology, and this is reflected in the GAINS model.

As an alternative to the country-to-region specific transfer matrices *T*, GAINS can also simply just use (regional) GWP or GTP coefficients and aggregate over different pollutants. The resulting impact function can then be used as the *RF* function in Section 4 below.

3.2 Carbon deposition

Input data and optimization routines have also been developed for carbon deposition on the Arctic and on Alpine glaciers.

$$CDep_k = \sum_i \sum_p T_{ik}^{CDep,p} \cdot E_{i,p} + k_{CDep}^k$$

where, as before, *i* are the source regions, *k* is the receptor region and the *p* are the relevant pollutants. The transfer matrices were actually calculated separately for dry and wet deposition. Figure 3 shows the values of the transfer matrices for BC and OC, for dry and wet carbon deposition in the Arctic region north of 70 degrees.

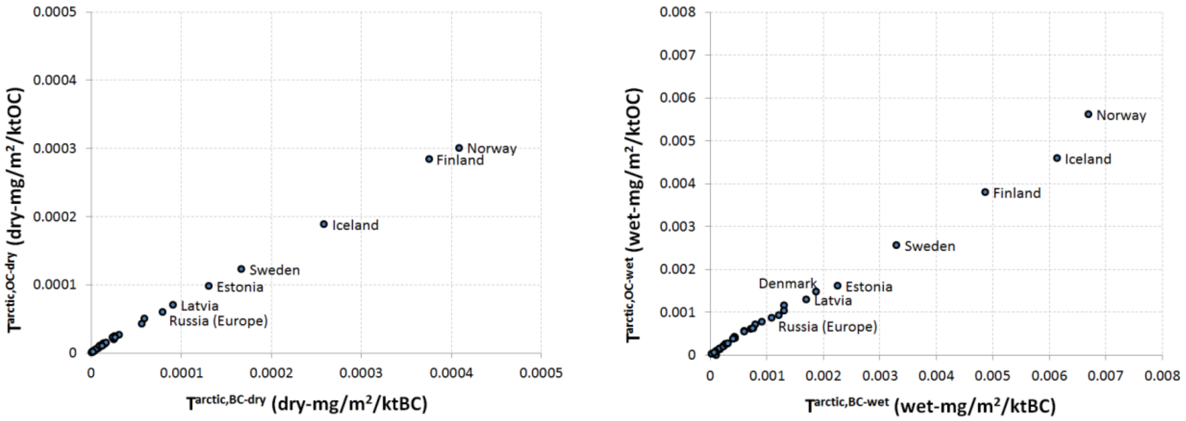


Figure 3 Transfer matrices for dry (left panel) and wet (right panel) carbon deposition to the arctic 70° N region. In general the wet deposition coefficients are larger than the dry ones, and the rates are higher for BC than those for OC.

4 Optimization

The GAINS model can be used to identify emission control strategies that reach defined environmental objectives in the most cost-effective way, i.e. by identifying portfolios of emission control technologies that achieve the objectives at lowest costs. The GAINS optimization is described in detail in (Wagner et al. 2013).

In the GAINS optimization the environmental targets are always made explicit by defining upper limits as constraints on the indicators $EnvImp_{\Omega,k}$ of the environmental impacts Ω (typically we consider several different indicators simultaneously):

$$EnvImp_{\Omega,k} \leq Target_{\Omega,k}$$

in this case for each receptor k. In joint optimizations targets are set simultaneously, and there exist many alternative approaches to systematically explore targets and to identify plausible combinations of targets.

Targets need to be feasible, i.e. within reach. A zero-impact goal is laudable, but often cannot be reached. There are technological constraints of various types (Wagner et al. 2013), so that anthropogenic emissions cannot be reduced to zero. Moreover, even with zero anthropogenic emissions the environmental impact indicators would not necessarily be zero. Thus, in order to ensure that the lowest possible values are estimated and that only feasible targets are considered, it is useful to first generate the maximum technically feasible reduction (MTFR) scenario, which represents the lowest achievable emission level under the given constraints. The range between the baseline (current legislation scenario) and the MTFR scenario is often called the feasible range or 'gap', and scenarios can be characterized by a number between 0% and 100% (the 'gap closure') describing where, within the feasible range, the scenario lies. Here 0% refers to the baseline scenario, and 100% to the MTFR scenario.

In general, target values between the baseline (current legislation) and MTFR level are feasible for any combination of target values on indicators whose transfer matrices have the same sign. For example, the eutrophication impact functions are linear functions in the emissions of NO_x, and the transfer coefficients of NO_x in these functions are positive. However, in the calculation of radiative forcing the NO_x coefficient is negative (NO_x through nitrate is cooling), hence there is a trade-off between targets on eutrophication and on radiative forcing.

A systematic analysis reveals that trade-offs and synergies exist between air pollution objectives for health and ecosystems on the one hand, and radiative forcing on the other. Figure 4 shows the implications of the gap closure procedure on the four impact indicators - years of life lost from $PM_{2.5}$ (YOLL), acidification, eutrophication and SOMO35 - on the radiative forcing over the EMEP region, calculated as described above, i.e. ignoring the ozone effect.

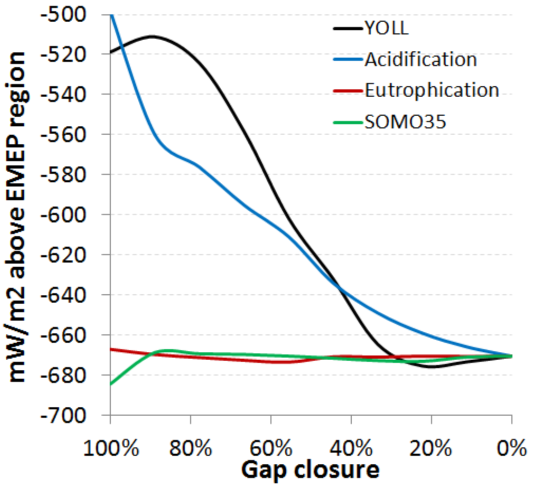


Figure 4 Radiative forcing from short-lived climate forcers over the EMEP modelling domain as a function of single impact gap closure targets

First, in Figure 4 note the range of RF values for these scenarios. All values lie between minus 500 and minus 700 milli-Watts per square meter (mW/m^2). The YOLL gap closure implies an initial reduction of the forcing (as a result of initial $PM_{2.5}$ and implied BC emission reduction), but then a steep increase (as a result of sulphur emission reductions), and finally a small decrease (as a result of further BC reductions). Similarly, a reduction in the acidification indicator is achieved cost-effectively by a reduction of SO_2 and NO_x, leading to a net increase in radiative forcing. Thus, these curves are the result of measures for different pollutants being taken at different ambition levels. Neither the reduction of the eutrophication nor, in this setup, the SOMO35 indicator, has significant impacts on the radiative forcing. We note, however, once again that the ozone effect is not adequately captured by the relations described above, and thus qualitatively different conclusions will be drawn when it is included in the calculations.

The above co-effect on regional radiative forcing depends on the domain that is considered. Figure 5 shows the radiative forcing changing in response to targets on YOLL, acidification, and eutrophication over four different domains (EMEP region, Northern Hemisphere (NH), Arctic region above 70 degrees, and Arctic region above 60 degrees). As expected, the relative impact over the EMEP region is largest, while the effect over the Northern hemisphere is small. The effect of the SOMO35 gap closure procedure on the radiative forcing is negligible and therefore not shown.

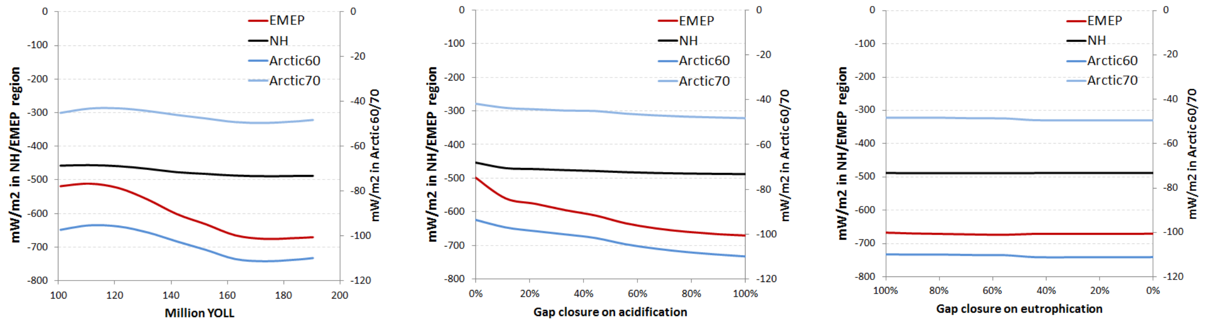


Figure 5 The effect of the single effect gap closure procedure on the radiative forcing over four regions.

The analysis of whether climate-related and non-climate related targets are compatible and how they influence the overall emission control costs can be extended and performed systematically. In Figure 6 we restrict ourselves to the relationship between the YOLL indicator, the radiative forcing over the EMEP domain and the emission control cost.

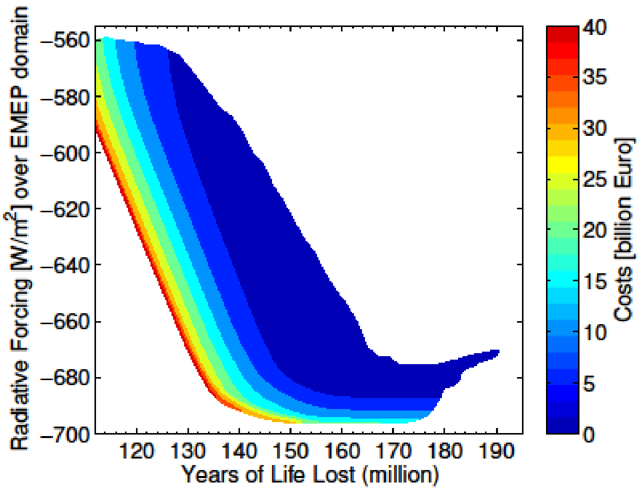


Figure 6 Additional cost for reaching a particular level of radiative forcing, given a YOLL level. The upper enveloping curve represents the cost-effective scenarios to reach a given YOLL level without constraint on the radiative forcing

The figure shows the lowest costs above baseline costs (colour) as a function of a joint YOLL and forcing target for the year 2020. The baseline is represented by the most eastern point of the coloured areas. There are white areas in the graph for three reasons. First, the area to the right of the baseline is white because GAINS will not increase emissions to higher than baseline levels, hence the YOLL indicator cannot be higher than in the baseline. Similarly, the area north of the highest coloured point (at around -560 mW/m^2 cannot be reached either, for this the (SO_2) emissions would have to be higher than in the baseline. Second, the area south of the coloured area is white because there are no feasible solutions in this area: it is simply not possible to reduce the radiative forcing below -696 mW/m^2, nor is it possible to reduce the YOLL indicator to the level of, say, 120 million YOLL, while keeping the forcing level at around -680 mW/m^2. Third, the area in the north and northeast corner is white because there are no cost-effective solutions located in this area. Thus, Figure 6 should be read in the following way:

- starting from the baseline scenario on the right, iteratively setting a stricter and stricter constraint on the YOLL indicator, and minimizing costs in each scenario, the resulting emission reductions lead to a change in radiative forcing such that all resulting scenarios are lying on the curve that envelops the coloured area on the upper end. This curve corresponds to the black curve in Figure 4 (The curve here looks more bumpy only because of a coarse graining in the graphical representation.)
- for a given level of the YOLL indicator (we have divided the range between baseline and lowest YOLL level into m=40 steps) we minimize the forcing indicator and obtain the lower enveloping curve;
- finally, at a given value of the YOLL indicator, the range between the lower and the upper enveloping curve is divided into n=25 steps, and for each step we minimize the cost to reach the n-value of the forcing indicator and the given value of the YOLL indicator. The colour code of each the 1,000 scenarios indicates the emission control cost above the baseline scenario.

Clearly, the environmentally 'desirable' directions in this graph are 'down' and 'left', i.e. lower health impacts and lower forcing. Thus, scenarios lying in the white area above the upper envelope are discarded, because they are not cost effective for a given target on the YOLL indicator: there are scenarios, at the same YOLL level, but with lower forcing *and* lower costs.

Figure 6 shows that within a moderate range of ambition levels on the YOLL (say, between 190 and 140 million YOLL), it is possible to find an alternative solution to the most cost-effective one which, at relatively low extra cost, achieves the same YOLL target, but keeps the radiative forcing below, say, -660 mW/m2. For more ambitious YOLL targets the costs increase steeply, and below 130 million YOLLs such a forcing level cannot be achieved. In summary, at moderate health ambition level the regional forcing can be kept at baseline level, i.e. with the caveats mentioned above (in particular the fact that here the ozone effect has been neglected) there is no significant trade-off between health and near-term, regional climate objectives.

Future analysis will include a systematic GAINS assessment of the synergies and trade-offs between environmental objectives (reduction of YOLL, eutrophication, acidification, SOMO35) and other climate-related indicators such as GWP and GTP over different time horizons.

5 New elements in GAINS to accommodate new metrics

Within the ECLIPSE project, a development of new and alternative metrics is one of the tasks. Use of such metrics should be possible within the GAINS model and therefore there might be a need for adjustments to the database structure or some of the calculation routines.

In the second half of 2013, we have received the first set of numbers representing new metrics for SLCPs. This metrics include GTP and GWP (for 20 and 100 years) values where different regional (Europe, China, Rest of the World) and seasonal (summer, winter) numbers are given. This new and unique metric will be described in detail in a separate deliverable within ECLIPSE.

Use of such metric required extension of the GAINS model to account for seasonality of emissions; the regional resolution in GAINS is already far more detailed than the three regions. We have collected various sets of data to develop seasonality in GAINS; current calculation provided annual totals. Not all sectors are characterized by strong seasonality but some like residential combustion, agriculture, fertilizer application, and in some areas also power plants have significant seasonality. Rather than defining share of emissions occurring in summer and winter, we have completed monthly data set and will be using it along with the new metrics to identify set of measures which lad to declining forcing while not aggravating air quality targets. A separate report/deliverable (eventually aiming at peer review paper) will be provided describing the set of measures developed with this metrics.

References

Amann M, Bertok I, Borken J, et al. (2008) GAINS-Asia: A tool to combat air pollution and climate change simultaneously; Methodology. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

Amann M, Bertok I, Borken-Kleefeld J, et al. (2011) Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications. EMS 26:1489–1501. doi: 10.1016/j.envsoft.2011.07.012

Cofala J, Amann M, Klimont Z, et al. (2007) Scenarios of Global Anthropogenic Emissions of Air Pollutants and Methane Until 2030. Atmospheric Environment Vol 41/38:8486–8499.

Höglund-Isaksson L (2012) Global anthropogenic methane emissions 2005-2030: technical mitigation potentials and costs. Atmos Chem Phys Discuss 11275–11315.

IPCC (2007) Climate Change 2007: Climate change. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Cambridge, UK and New York, USA

Isaksen ISA, Granier C, Myhre G, et al. (2009) Atmospheric Composition Change: Climate-Chemistry Interactions. Atmospheric Environment 43:5138–5192. doi: 10.1016/j.atmosenv.2009.08.003

Klimont Z, Cofala J, Xing J, et al. (2009) Projections of SO2, NOx, and carbonaceous aerosols emissions in Asia. Tellus 61B:602–617. doi: DOI: 10.1111/j.1600-0889.2009.00428.x

Myhre G, Berglen TF, Johnsrud M, et al. (2009) Modelled radiative forcing of the direct aerosol effect with multi-observation evaluation. Atmos Chem Phys 9:1365–1392. doi: 10.5194/acp-9-1365-2009

UNEP/WMO (2011) Integrated Assessment of Black Carbon and Troposheric Ozone. 285.

Wagner F, Heyes C, Klimont Z, Schoepp W (2013) The GAINS optimzation module: Identifying cost-effective measures for improving air quality and short-term climate forcing. IIASA, Laxenburg, Austria

Wei W, Wang S, Chatani S, et al. (2008) Emission and speciation of non-methane volatile organic compounds from anthropogenic sources in China. Atmospheric Environment 42:4976–4988. doi: 10.1016/j.atmosenv.2008.02.044