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Extension of the GAINS model to include short-lived climate forcers

Final Report

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Abstract

This paper presents a first implementation of a new module to calculate the impacts of emission reductions of air pollutants on radiative forcing into IIASA's GAINS (Greenhouse gas – Air pollution Interactions and Synergies) model. The approach extends the multi-pollutant/multi-effect approach of the GAINS model that has been used for air pollution impacts (i.e., human health and ecosystems impacts) to also consider impacts on near-term climate change from emissions of five short-lived substances.

For the initial implementation presented in this report source-receptor relationships have been developed that quantify the impacts of reductions of the various emission substances in each European country on instantaneous radiative forcing, calculated over the northern Hemisphere, the EMEP model domain, the Arctic and Alpine glaciers. These source-receptor relationships have been derived from calculations of the EMEP Eulerian atmospheric dispersion model, and employed normalized radiative forcing in each grid cell as estimated by CICERO.

The GAINS optimization module has been extended such that (a) radiative forcing for different target regions resulting from emission reductions that are optimized for health and environmental impacts of air pollutants can be calculated, (b) radiative forcing can be introduced as a separate constraint in the optimization (replacing targets for health and environmental impacts of air pollutants), and (c) combined strategies that meet constraints on radiative forcing as well as on health and environmental impacts at least costs can be identified. A sample of initial calculations is presented in this report, illustrating the relations between different environmental targets and radiative forcing. It turns out that in general cost-effective improvements of health impacts from PM2.5 and of acidification will increase radiative forcing by up to 150-200 mWm^{-2} in the EMEP region. In contrast, improvements in eutrophication will hardly affect radiative forcing. Furthermore, there are cheap ways to avoid some of the trade-offs between health effect and radiative forcing targets.

This initial analysis focuses on instantaneous radiative forcing over the EMEP domain. Input data and optimization routines have also been developed for carbon deposition on the Arctic and on Alpine glaciers. Analysis of the impacts of alternative emission control scenarios on these receptor regions, and optimization for such targets, will require additional work.

It needs to be emphasized that the current analysis is based on an initial data set of the impacts of radiative forcing, which only considers the direct effects of aerosols on radiative forcing. It does not include indirect effects of aerosols (for which an accurate quantification is burdened with significant uncertainties), and ignores changes in radiative forcing that result from changes in ozone burdens in the atmosphere caused by cuts of NO_x and VOC emissions.

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Introduction

Short-lived climate forcers (SLCFs), i.e., aerosols and greenhouse gases with relatively short atmospheric lifetimes, affect the earth's radiative balance either directly through their radiative properties or indirectly through their interaction with clouds. As a result of their potential effect on climate change on a short timescale – compared to that of long-lived greenhouse gases – there is increasing interest in research into their emissions, distributions and effects.

The feasibility of including near-term climate impacts as an additional effect of air pollutants under the LRTAP Convention was discussed at a Science/Policy Workshop on Air Pollution and Climate Change organised by the Swedish EPA in Gothenburg in October 2009. Subsequently, in a collaborative effort involving the Center for International Climate and Environmental Research – Oslo (CICERO), the University of Oslo (UiO), EMEP's Meteorological Synthesising Centre – West and the Centre for Integrated Assessment Modelling (CIAM) at IIASA, a plan to take this proposal further was initiated. Its specific purpose is to assess the technical feasibility of extending the GAINS model optimisation used within the LRTAP Convention such that the radiative effects of SLCFs are also taken into account in the search for cost-effective solutions (see Table 1).

	PM (BC, OC)	SO_2	NO_x	VOC	NH_3	CO	CO_2	CH_4	N_2O	HFCs PFCs SF_6
Health impacts: PM (Loss in life expectancy)	√	√	√	√	√					
O_3 (Premature mortality)			√	√		√		√		
Vegetation damage: O_3 (AOT40/fluxes)			√	√		√		√		
Acidification (Excess of critical loads)		√	√		√					
Eutrophication (Excess of critical loads)			√		√					
Climate impacts: Long-term (GWP100)							√	√	√	√
Near-term forcing (in Europe and global mean forcing)	√	√	√	√	√	√				
Black carbon deposition to the arctic	√									

Table 1: Introduction of climate impacts into the GAINS multi-pollutant/multi-effect framework as an additional effect of air pollutants.

Currently, attention has been focussed on radiative forcing (radiative forcing) as an appropriate metric to consider when including aspects of climate forcing in the GAINS analysis. Radiative forcing is defined as the change in the net- downward minus upward – irradiance (expressed in Wm^{-2}) at the tropopause due to a change in an external driver of climate change.

In the present study, the EMEP global chemistry transport model is used to establish the relation between emission changes in European countries and the response of the atmosphere. The resulting radiative forcing is to be assessed with the help of normalised radiative forcing factors provided by CICERO. This report gives a brief description of the progress made to date towards the inclusion of radiative forcing within the GAINS multi-pollutant/multi-effect framework, and presents first results on cost-effective emission control scenarios that consider radiative forcing as a side-effect or as an additional environmental target, in addition to human health and vegetation impacts. Calculations presented in this report demonstrate the new functionality of the extended GAINS framework and identify some basic response patterns. However, robust policy advice will require more in-depth analyses of the interactions between different environmental targets, of the uncertainties inherent in these initial quantifications of radiative forcing, and the potential strategic implications on air quality and climate policies.

EMEP Modelling

The global version of the Unified EMEP model has been used to calculate tropospheric aerosol burdens and the contributions of emissions from individual EMEP countries to the column burdens.

These SLCF model runs used a new global emission data set with a resolution of 1° x 1°. For European sources the EMEP emission inventory for 2006 was employed. These data, which include $PM_{2.5}$ and PM_{10} emissions, were supplemented by estimates of OC, BC and their ratios to $PM_{2.5}$, so that the necessary BC and OC inputs would be available to the model. The BC and OC data were generated with the GAINS model, and provided by IIASA at the SNAP1 sector level for each European country. For emission sources outside Europe the EMEP calculations made use of data from the RCP 8.5 scenario (Riahi *et al.*, 2007) for 2005.

Calculations were carried out using the meteorological conditions of 2006.

Further details of the EMEP model set-up and specific information on the modelling of aerosols (see also Tsyro *et al.*, 2007) can be found in EMEP, 2010.

Source-receptor calculations were performed to assess the influence of emissions from each European country on global aerosol loading. For each source region in turn, a set of four reduction scenarios was carried out, in each of which emissions of one pollutant, or set of pollutants, was reduced by 15%. The pollutants considered in this way were SO_2, NH_3 and nmVOC taken individually, and NO_x, BC and OC where the emission reductions could be made simultaneously because of the lack of interaction between them in the model.

The results of such model calculations, involving some fifty separate European source regions, have been made available to IIASA on a 1° x 1° grid covering the globe. The model outputs provided cover a wide range of parameters in addition to the relevant surface concentrations and column burdens, and have been given as both annual and monthly values.

Normalised Radiative Forcing

Normalised radiative forcing factors, i.e., the radiative forcing (Wm^{-2}) divided by the total column burden of a species (gm^{-2}), can be used to estimate radiative forcing from the column burden results of the EMEP model. Such factors can be calculated using radiative transfer models developed over several years at UiO/CICERO. Results have been provided by CICERO for BC, OC, SO_4 and NO_3 components – so far as annual averages – on a 1° x 1° grid corresponding to the global EMEP model output. These data are based on calculations with the global chemical transport model OsloCTM2, described by Myhre *et al.*, 2009.

Source-receptor matrices

We have processed the EMEP model results and incorporated them into the GAINS databases, as well as developed and tested transfer coefficients relating changes in radiative forcing to emission changes in European source regions, i.e. source-receptor relationships for radiative forcing. This also involved the definition of appropriate geographical regions over which the estimated radiative forcing should be integrated in order to provide results at a relevant and meaningful level.

In GAINS, the data for the Northern Hemisphere have been combined with the normalized radiative forcing factors provided by CICERO to calculate linear transfer coefficients (Wm^{-2} kt^{-1}) that give the incremental change in area-weighted radiative forcing for each component in a given region per kt of pollutant. 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 radiative forcing in these regions (for those aspects of radiative forcing included in this assessment) for any particular emissions scenario.

By way of illustration, Figure 1 shows the impact of emissions of 1000 tons of BC on instantaneous forcing over the Northern Hemisphere, EMEP domain and Arctic, defined as the area above 70°N. Red marks indicate Arctic Council countries, showing their growing relative importance when the domain is reduced to Arctic.

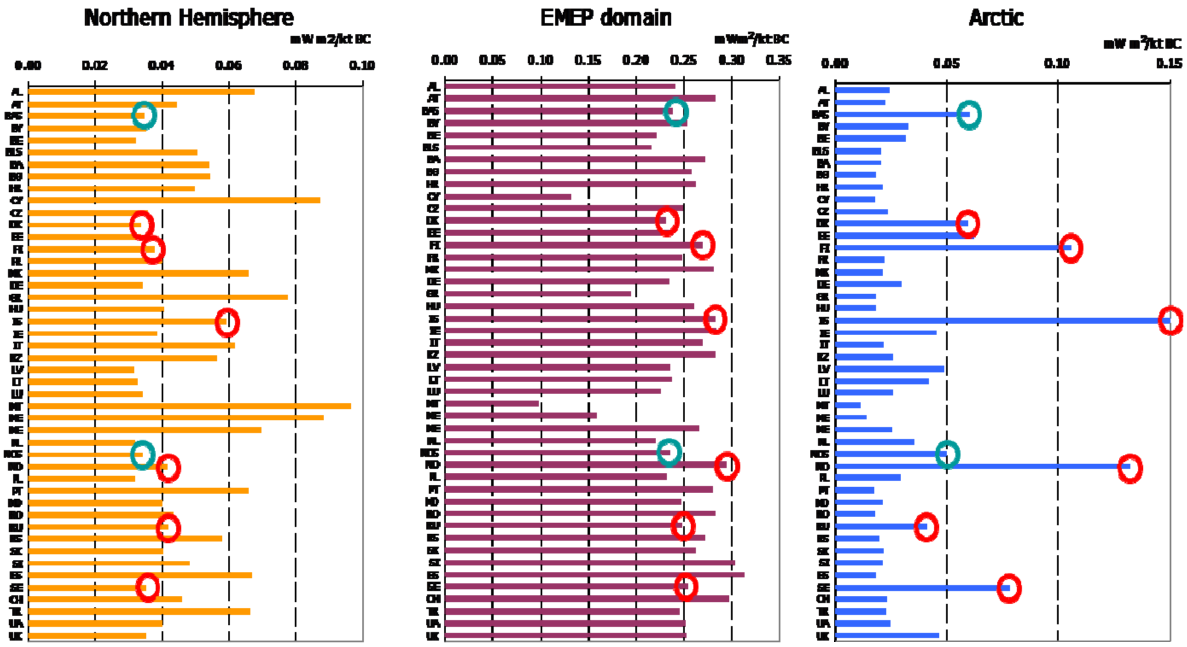

Figure 1: Impact on instantaneous forcing of 1 kt BC over different domains; Marked regions include Arctic Council countries (red) and two sea regions (green) – Baltic Sea and North Sea, mW m^{2} kt BC^{-1} ; Source: EMEP/MSC-W

IIASA has also developed a first control scenario that explored the impacts of emission reductions beyond the current legislation case. This scenario assumes the selection of options for which the radiative forcing value is lower than for the no-control situation considering all co-emitted species. The selection was made using global warming potentials (GWP) from IPCC AR4. The scenario includes the following key control categories:

- DPF on road and non-road machinery
- Pellet stoves
- End of pipe in industry
- End of pipe on small boilers

Figure 2 illustrates the impact of this scenario on forcing over the Arctic region along with the comparable calculations performed for the year 2005 and for the baseline scenario (CLE).

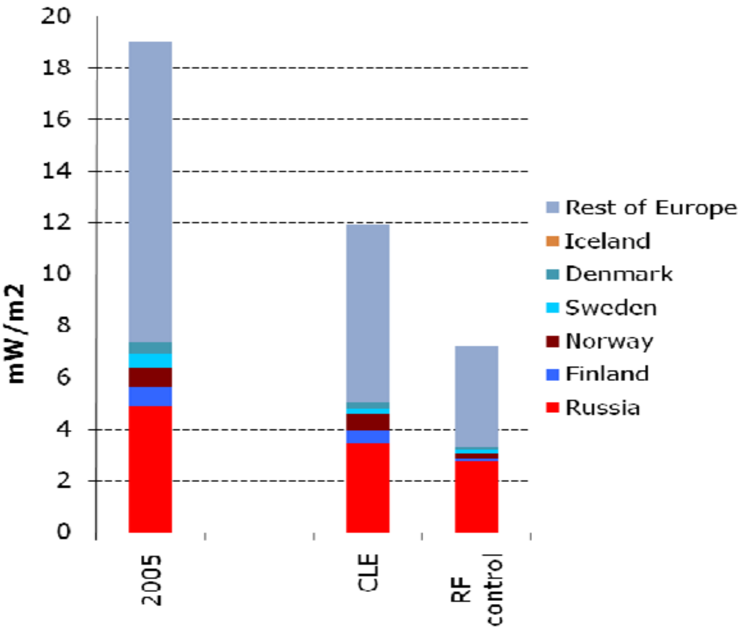

Figure 2: Country contributions to forcing over the Arctic domain (>70 ^{o} N).

Introduction of Radiative Forcing into the GAINS Optimization:

Methodology

We have extended the GAINS optimization framework to include radiative forcing as an additional effect of air pollutants and greenhouse gases, so that near-term radiative forcing can be addressed within the optimization process – in addition to the existing health and environmental impacts – either as an extra constraint or in a multi-objective fashion. For this purpose we employ the radiative forcing transfer coefficients and related data that are described above.

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. We thus write:

$$RF_r = \sum_s \sum_p T_{r,s}^{RF,p} \cdot Em_{s,p} + k_r^{RF}$$

where r is the receptor region, s the source region, p the relevant pollutants, $Em_{s,p}$ the emissions of pollutant p in source region s, with transfer matrix $T_{r,s}^{RF,p}$ and constants $k_r^{RF}$for radiative forcing. The average forcing is calculated for four distinct receptor regions (EMEP domain, Northern Hemisphere, 70+ degree arctic region, and 60+ degree arctic region).

We have also implemented the corresponding calculations of carbon deposition on snow-covered regions, in obvious analogy to the above:

$$C - Dep_r = \sum_s \sum_p T_{r,s}^{C-Dep,p} \cdot Em_{s,p} + k_r^{C-Dep}$$

where the relevant set of pollutants here only includes BC and OC, and only three distinct receptor regions are considered (the Alps, 70+ degree arctic region, and 60+ degree arctic region). Constraints on these impact indicators can now be combined with other target setting approaches in the GAINS model to calculate joint optimized scenarios. The targets are linked through the above equations to the cost function through the emissions and costs for emission reduction measures.

Initial Results

As a first step, we explore the changes in radiative forcing over the EMEP domain that result from the emission reductions in the EMEP domain that result from the implementation of current legislation in the year 2020 (compared to the year 2020) and of the maximum feasible emission reductions (Figure 3). Implementation of the air quality measures contained in the current legislation, as well as the full implementation of all available air quality measures, will reduce the net negative forcing of European emissions, that is, it will increase radiative forcing by up to 0.4 W.m-2 compared to the year 2000. In contrast, a targeted selection of measures that reduce forcing (and elimination of measures that increase forcing) could improve air quality without leading to additional warming.

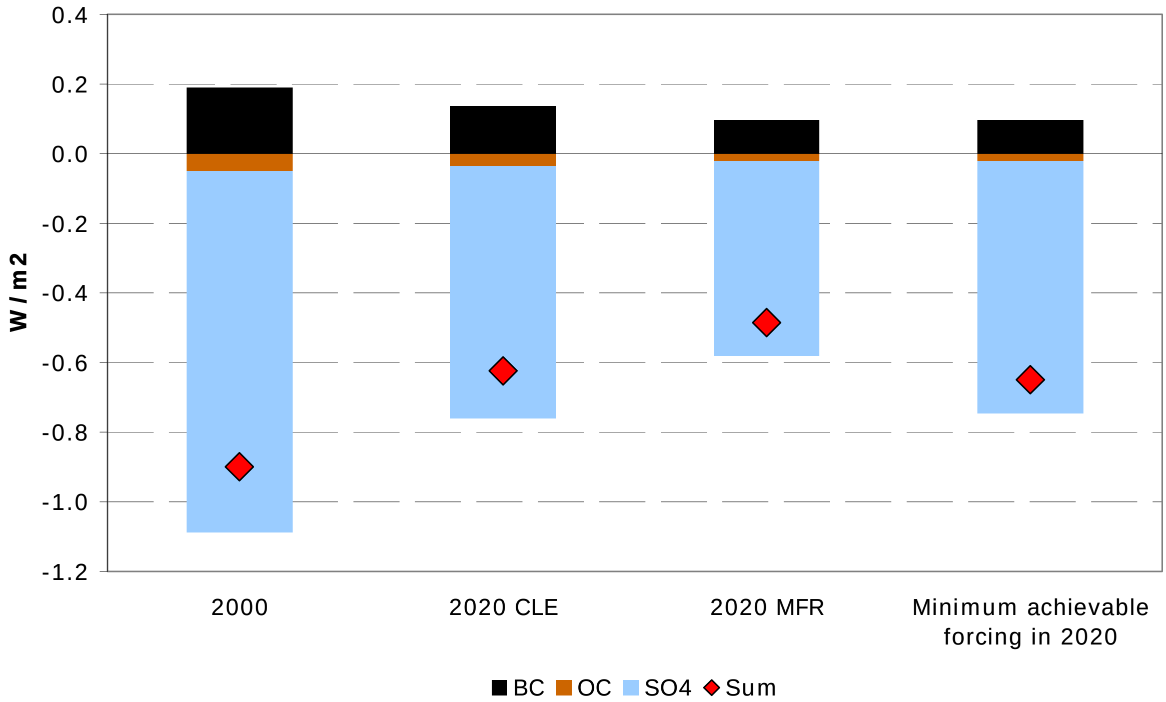

Figure 3: Radiative forcing over the EMEP domain from the emissions of the countries in the EMEP domain for the year 2000, the current legislation case for the year 2020, the maximum feasible reductions in 2020, and the minimum forcing that is achievable in 2020 by a targeted selection of measures that reduce radiative forcing.

Let us next illustrate some of the initial results of the optimization. First, with the new extension we can now calculate the radiative forcing in the various receptor regions resulting from a cost-optimization for air quality targets, e.g. for a health target to reduce human exposure to PM2.5 (Figure 4). With progressing stringency of the health target (in this case quantified through the YOLL (Years of Life Lost) indicator), first the radiative forcing declines too as a result of a reduction in BC and thus PM2.5 as well. Then, as the YOLL target becomes more stringent, the radiative forcing increases as a result of the measures to cut SO2 and NOx emissions. Finally, for YOLL targets close to the maximum feasible reduction, the radiative forcing is being reduced again by a small amount, as also the costly BC measures are taken to further reduce YOLLs.

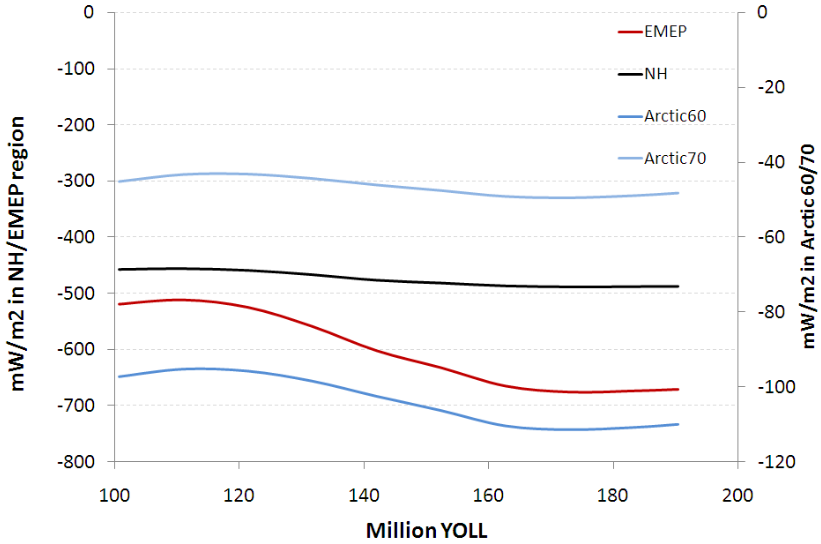

Figure 4: Radiative forcing in four regions, resulting from a cost-effective Europe-wide reduction in the YOLL health indicator.

Similarly we have calculated the implications of cost-effective reductions in acidification and eutrophication on the radiative forcing in the four receptor regions (Figure 5). For setting environmental targets on a country-by-country level we have applied the gap closure procedure as in the CAFE program. While the setting of acidification targets has some influence on the radiative forcing, in particular over the EMEP domain, the effect of eutrophication targets is rather small, as could be expected.

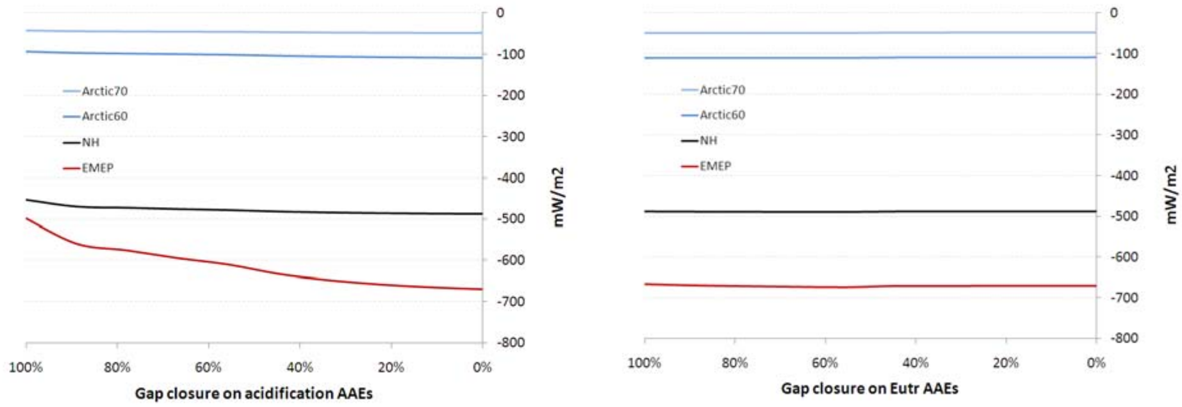

Figure 5: Radiative focing in four receptor regions as a result of a cost-effective gap closure on the accumulated area exceedance (AAE) indicator in each country, for acidification (left) and eutrophication (right).

For a specific receptor domain (here: the EMEP region) Figure 6 compares the impact on radiative forcing of cost-effective responses to individual environmental targets, all expressed as gap closure percentages.

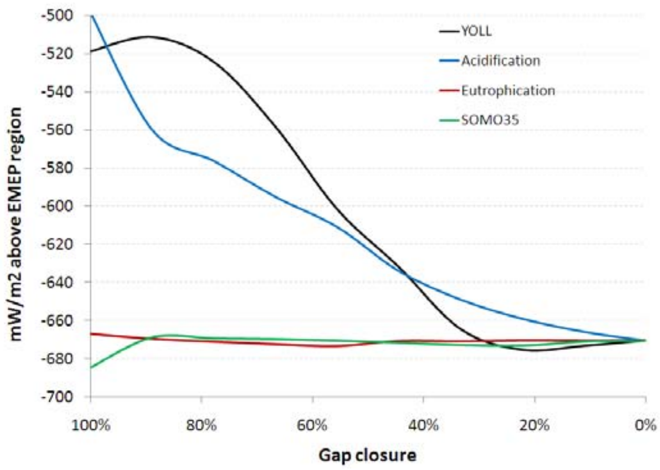

Figure 6: Radiative forcing over the EMEP domain as a results of cost-effective responses to individual environmental targets, all expressed as gap closure between CLE and maximum feasible reductions.

With these extensions, GAINS can now be used not only to simulate the implications of environmental targets on radiative forcing, but we can also include radiative forcing as an endpoint (constraint) for the optimization on which in turn a target can be imposed. In order to do so we first can identify the range of possible radiative forcing targets. This range depends on the ambition level of the other environmental targets, because radiative forcing and the other impact indicators are linked through the emissions of the relevant pollutants and are thus not independent. For example, Figure 7 shows how the feasible range of radiative forcing values depends on the ambition level of the YOLL indicator. Close to the CLE scenario on the right hand side the range of feasible radiative forcing values is larger than on the left hand side where we are closer to the maximum feasible reduction (here understood as a maximum reduction in YOLL): a low YOLL target value can only be met with reductions in SO_2 (PM), which in turn increases (decreases) radiative forcing and thus restricts the range of feasible values on radiative forcing. The dark line in the middle of Figure 7 represents the radiative forcing values as a result of the cost-optimal response to the YOLL target; thus, values above that curve are economically inefficient and can be ignored in practical applications.

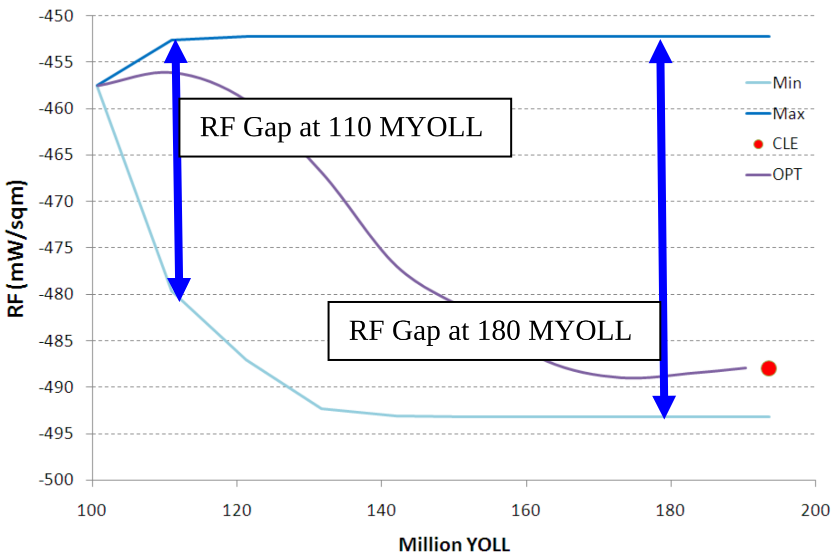

Figure 7: Range of feasible radiative forcing values for given level of YOLL.

As mentioned above the optimization framework can also be used to find cost-effective solutions when both radiative forcing and environmental targets are imposed simultaneously. As an illustration we consider the range between 120 and 150 million YOLL and between a radiative forcing between 461 and 481 mW/m^2 above the EMEP domain, and plot the costs of the cost-minimal solution that achieves both targets.

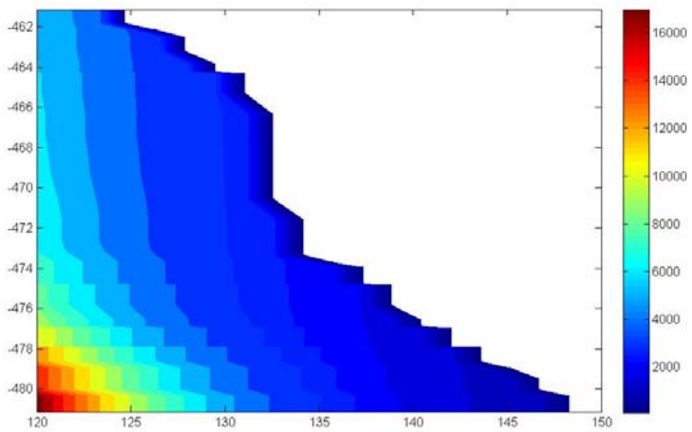

Figure 8: Minimal cost for joint targets on YOLLs (horizontal axis) and radiative forcing over the EMEP region (vertical axis), in units of million of Euros.

We observe that for a given YOLL level there is a potential for reducing radiative forcing at little or no cost. That is, in Figure 8, starting at the top and moving downwards in a vertical line initially does not increase the costs significantly. This can be investigated systematically, as shown in Figure 9. Thus, the cost curves for reducing radiative forcing at a given level of YOLL are rather flat, i.e. reducing the level of radiative forcing by around 10 mW/m^2 from the right hand side does not increase the costs significantly.

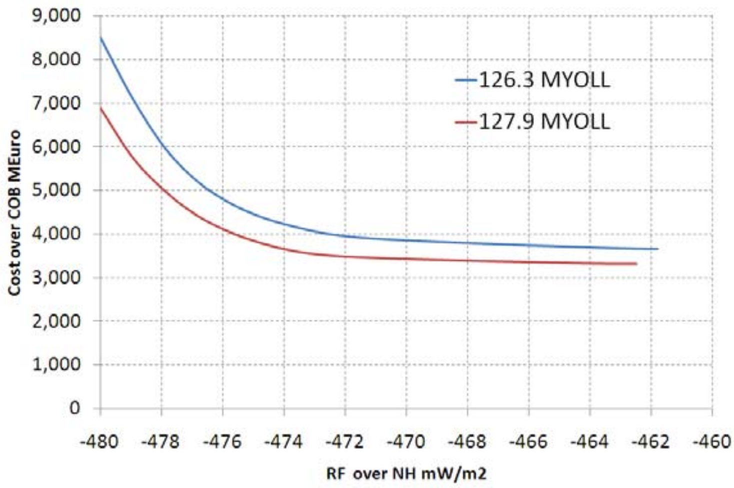

Figure 9: Costs above the baseline level for increasingly ambitious radiative forcing targets for two distinct levels of YOLL (million of Euros).

There are other interesting questions one can address within the optimization framework. For example, while we have observed changes in radiative forcing as a result of a cost-optimal response to a YOLL target, we may also calculate the cost-optimal response to a YOLL target, given that a certain radiative forcing level (e.g. the CLE level) is not exceeded. Figure 10 shows that down to a level of around 150 MYOLL this CLE radiative forcing target does not increase costs significantly relative to the case without the radiative forcing target. For more ambitious YOLL targets, however, there is a clear, economically quantifiable trade-off with the radiative forcing constraint, and finally – as could already be seen from Figure 7 – a YOLL reduction below around 120 MYOLL, while keeping the radiative forcing baseline level, is not possible.

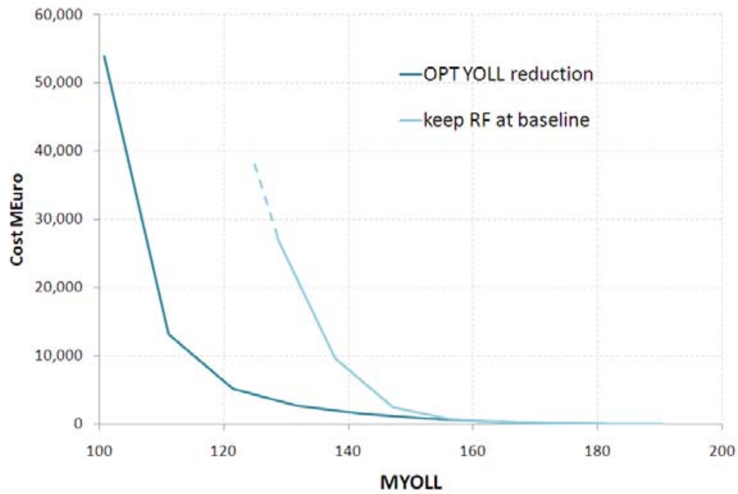

Figure 10: Costs of the least-cost solution to a YOLL target (horizontal axis) without constraints on radiative forcing (dark line) and requiring that radiative forcing remains at the baseline level (light blue line).

Finally we note that of course the optimization routine delivers for any feasible configuration of targets all GAINS scenario details for each country, i.e., costs, emissions, control strategies, etc, so that each scenario can also be analyzed in detail.

Conclusions

This paper presents a first implementation of a new module to calculate the impacts of emission reductions of air pollutants on radiative forcing into IIASA's GAINS (Greenhouse gas – Air pollution Interactions and Synergies) model. The approach extends the multi-pollutant/multi-effect approach of the GAINS model that has been used for air pollution impacts (i.e., human health and ecosystems impacts) to also consider impacts on near-term climate change from emissions of five short-lived substances.

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