GREENHOUSE GAS–AIR POLLUTION INTERACTIONS AND SYNERGIES

GAINS ASIA

A TOOL TO COMBAT AIR POLLUTION AND CLIMATE CHANGE SIMULTANEOUSLY

METHODOLOGY

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SIXTH FRAMEWORK PROGRAMME

The GAINS-Asia model integrates a number of established economic and environmental models developed by international experts at the following institutions:

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ERI
Energy Research Institute
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TERI
The Energy and Resources Institute
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Executive summary

This report provides a documentation of the methodology of the GAINS-Asia model.

Current and future economic growth in China will counteract ongoing efforts to improve air quality through controls of sulphur dioxide (SO_2) emissions from large stationary sources and nitrogen oxide (NO_x) emissions from vehicles. Unless further air pollution policies are implemented, the increase in coal consumption to fuel additional industrial production and provide more electricity to a wealthier population will largely compensate the positive effects of current efforts to control SO_2 emissions in China. Lacking regulations for controlling emissions of NO_x from

For policymakers, industry, NGOs and researchers wishing for more information and to conduct independent analyses, the GAINS-Asia model and documentation is freely available online at http://gains.iiasa.ac.at

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About the authors

This report is the result of cooperation between scientists at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria, the Energy Research Institute (ERI) in Beijing, China, and the Tsinghua University, Beijing, China.

At IIASA, the work was carried out by team of IIASA's Atmospheric Pollution and Economic Development programme, led by Markus Amann. Team members include Imrich Bertok, Jens Borken, Janusz Cofala, Chris Heyes, Lena Hoglund, Zbigniew Klimont, Pallav Purohit, Peter Rafaj, Wolfgang Schöpp, Geza Toth, Fabian Wagner and Wilfried Winiwarter.

1 Introduction

For a number of historic reasons, response strategies to air pollution and climate change are often addressed by different policy institutions. However, there is growing recognition that a comprehensive and combined analysis of air pollution and climate change could reveal important synergies of emission control measures (Swart *et al.*, 2004), which could be of high policy relevance. Insight into the multiple benefits of control measures could make emission controls economically more viable, both in industrialized and developing countries. While scientific understanding on many individual aspects of air pollution and climate change has considerably increased in the last years, little attention has been paid to a holistic analysis of the interactions between both problems.

The Greenhouse gas – Air pollution Interactions and Synergies (GAINS) model has been developed as a tool to identify emission control strategies that achieve given targets on air quality and greenhouse gas emissions at least costs. GAINS considers measures for the full range of precursor emissions that cause negative effects on human health via the exposure of fine particles and ground-level ozone, damage to vegetation via excess deposition of acidifying and eutrophying compounds, as well as the six greenhouse gases considered in the Kyoto protocol. In addition, it also considers how specific mitigation measures simultaneously influence different pollutants. Thereby, GAINS allows for a comprehensive and combined analysis of air pollution and climate change mitigation strategies, which reveals important synergies and trade-offs between these policy areas.

IIASA's Greenhouse gas – Air Pollution Interactions and Synergies (GAINS) model explores synergies and trade-offs between the control of local and regional air pollution and the mitigation of global greenhouse gas emissions. GAINS estimates emissions, mitigation potentials and costs for six air pollutants (SO_2, NO_x, PM, NH_3, VOC) and for the six greenhouse gases included in the Kyoto protocol. GAINS quantifies the technical and economic interactions between mitigation measures for the considered air pollutants and greenhouse gases. It assesses the simultaneous impacts of emission reductions on air pollution (i.e., shortening of statistical life expectancy due to the human exposure to PM2.5, premature mortality related to ground-level ozone, protection of vegetation against harmful effects of acidification and excess nitrogen deposition) as well as for selected metrics of greenhouse gases (e.g., the global warming potentials). Thereby GAINS explores the full effect of reducing air pollutants and/or greenhouse gases on all these endpoints. In addition, GAINS includes an optimization approach that allows the search for least-cost combination of mitigation measures for air pollutants and/or greenhouse gases that meet user-specified constraints (policy targets) for each of the environmental endpoints listed above. Thereby, GAINS can identify mitigation strategies that achieve air quality and greenhouse gas related targets simultaneously at least cost.

This report provides a documentation of the methodology that is applied for the GAINS model.

2 General approach of the GAINS model

IIASA's Greenhouse gas – Air Pollution Interactions and Synergies (GAINS) model explores synergies and trade-offs between the control of local and regional air pollution and the mitigation of global greenhouse gas emissions. GAINS estimates emissions, mitigation potentials and costs for six air pollutants (SO_2, NO_x, PM, NH_3, VOC) and for the six greenhouse gases included in the Kyoto protocol. GAINS quantifies the technical and economic interactions between mitigation measures for the considered air pollutants and greenhouse gases. It assesses the simultaneous impacts of emission reductions on air pollution (i.e., shortening of statistical life expectancy due to the human exposure to PM2.5, premature mortality related to ground-level ozone, protection of vegetation against harmful effects of acidification and excess nitrogen deposition) as well as for selected metrics of greenhouse gases (e.g., the global warming potentials). Thereby GAINS explores the full effect of reducing air pollutants and/or greenhouse gases on all these endpoints. In addition, GAINS includes an optimization approach that allows the search for least-cost combination of mitigation measures for air pollutants and/or greenhouse gases that meet user-specified constraints (policy targets) for each of the environmental endpoints listed above. Thereby, GAINS can identify mitigation strategies that achieve air quality and greenhouse gas related targets simultaneously at least cost.

	PM	SO_2	NO_x	VOC	NH_3	CO_2	CH_4	N_2O	HFCs PFCs SF_6
Health impacts: PM	√	√	√	√	√				
O_3			√	√			√		
Vegetation damage: O_3			√	√			√		
Acidification		√	√		√				
Eutrophication			√		√				
Radiative forcing: - direct						√	√	√	√
- via aerosols	√	√	√	√	√				
- via OH			√	√			√		

Figure 2.1: The GAINS multi-pollutant/multi-effect framework

The GAINS model framework makes it possible to estimate, for a given energy- and agricultural scenario, the costs and environmental effects of user-specified emission control policies (the "scenario analysis" mode), see Figure 2.2. Furthermore, an optimisation mode can be used to identify the cost-minimal combination of emission controls meeting user-supplied targets on air quality and/or greenhouse gas emissions, taking into account regional differences in emission control costs and atmospheric dispersion characteristics. The optimisation capability of GAINS enables the development of multi-pollutant, multi-effect pollution control strategies. In particular, the optimisation can be used to search for cost-minimal balances of controls of the 12 pollutants (SO_2, NO_x, VOC, NH_3, primary $PM_{2,5}$, primary $PM_{10-2.5}$ (= PM coarse), CO_2, CH_4, N_2O, HFC, PFC, SF_6) over the various economic sectors in all European countries that simultaneously achieve user-specified targets for human health impacts (e.g., expressed in terms of reduced life expectancy), ecosystems protection (e.g., expressed in terms of excess acid and nitrogen deposition), maximum allowed violations of WHO guideline values for ground-level ozone, and a basket of greenhouse gas emissions (Figure 2.2).

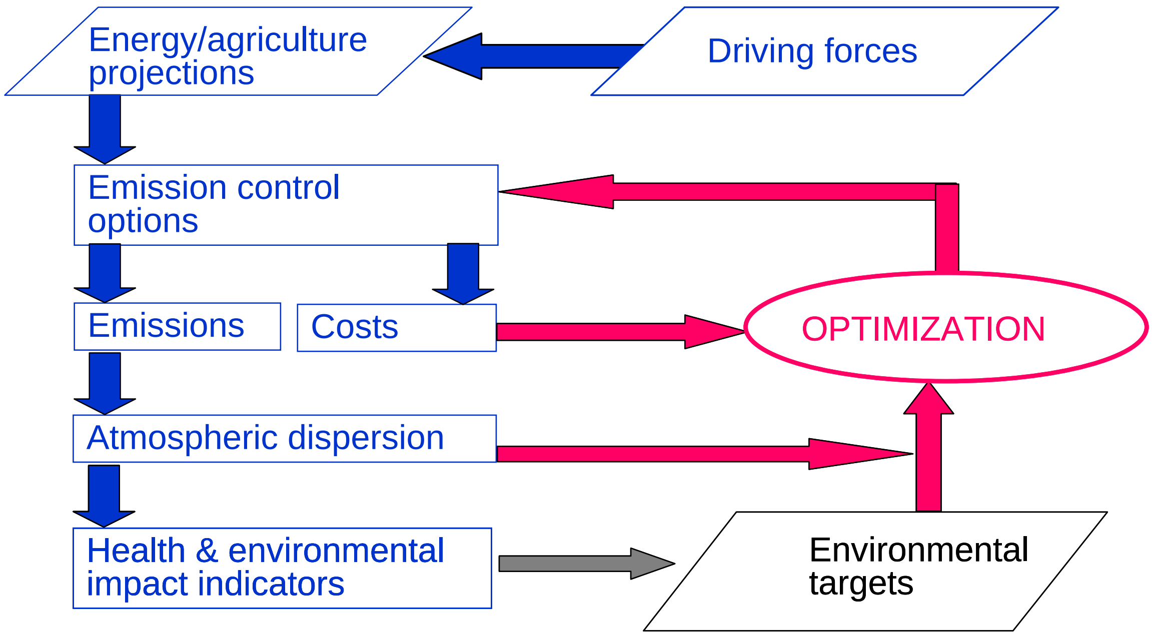


Figure 2.2: The iterative concept of the GAINS optimisation.

While the scenario analysis mode can be used to illustrate the economic and environmental consequences of an exogenously assumed pattern of emission controls, the optimisation feature allows the systematic identification of the least-cost allocation of emission controls that meet exogenously determined environmental targets for air pollution and greenhouse gas emissions.

With the scenario mode, the number of "what-if" scenarios that can be explored with the GAINS model is limited, which makes it impossible to fully explore the consequences of even the most important permutations of emission control measures in all economic sectors of all regions. In practice, such scenarios address a limited number of technology-related emission control rationales, but they cannot deliver a systematic analysis of environmentally driven emission control strategies.

Thus, the optimisation concept provides an important element of a "science based" rationale as a basis for emission reduction accords. By calculating country- and sector-specific reduction requirements for any exogenously specified environmental target, the GAINS optimisation can provide results that are of immediate relevance to negotiators because they meet the spatial and temporal scales that are relevant for decision makers. The optimisation is also attractive because, while striving for a common target (e.g., equal environmental improvement for all Parties), it considers environmental and economic differences between Parties that lead to objectively justifiable differences in abatement efforts. Resulting inequities in abatement burdens are based on scientifically determined differences in environmental sensitivities, atmospheric dispersion characteristics or emission source structures.

It is also important that the optimisation problem as set up in the GAINS model does not provide an absolute and unique answer to the pollution control problem. Actual results of an optimisation run depend on the environmental objectives (e.g., the acceptable environmental risk) as established by the negotiators, the goal function (minimization of total emission control costs), and the problem framing (e.g., the exclusion of changes in the energy systems, which cannot be directly influenced by environmental policies in Europe). All these settings are subject to negotiations, and the optimisation results are critically influenced by the policy choices on these issues. Thus, the GAINS model does not internalise policy choices, but deliberately leaves room for policy decisions.

3 Emissions and mitigation potentials

3.1 Emission estimates

For each of the pollutants listed in Figure 2.1, GAINS estimates emissions based on activity data, uncontrolled emission factors, the removal efficiency of emission control measures and the extent to which such measures are applied:

$$E_{i,p} = \sum_k \sum_m A_{i,k} ef_{i,k,m,p} x_{i,k,m,p} \tag{1}$$

where:

i, k, m, p	Country, activity type, abatement measure, pollutant, respectively
$E_{i,p}$	Emissions of pollutant *p* (for SO_2, NO_x, VOC, NH_3, PM2.5, CO_2 , CH_4, N_2O, etc.) in country *i*
$A_{i,k}$	Activity level of type *k* (e.g., coal consumption in power plants) in country *i*
$ef_{i,k,m,p}$	Emission factor of pollutant *p* for activity *k* in country *i* after application of control measure *m*
$x_{i,k,m,p}$	Share of total activity of type *k* in country *i* to which a control measure *m* for pollutant *p* is applied.

For calculating total greenhouse gas emissions, the GAINS model uses the global warming potentials defined in the Kyoto protocol (Table 3-1).

Table 3-1: Global warming potentials (GWPs) over 100 years used in GAINS emission calculations (UNFCCC, 1997)

Gas/sector	Gas	Average GWP
Carbon dioxide	CO_2	1
Methane	CH_4	21
Nitrous oxide	N_2O	310
HCFC-22 production	HFC	11700
Industrial refrigeration	HFC	2600
Commercial refrigeration	HFC	2726
Transport refrigeration	HFC	2000
Domestic refrigeration	HFC	1300
Stationary air conditioning	HFC	1670
Mobile air conditioning	HFC	1300
Aerosols	HFC	1300
Other HFC	HFC	815-1300
Primary aluminium production	HFC	6500-9200
Semiconductor industry	HFC	6500
High and mid voltage switches	SF_6	23900
Magnesium production and casting	SF_6	23900
Other use of SF_6	SF_6	23900

This approach allows capturing critical differences across economic sectors and countries that could justify differentiated emission reduction requirements in a cost-effective strategy. It reflects structural differences in emission sources through country-specific activity levels. It represents major differences in emission characteristics of specific sources and fuels through source-specific emission factors, which account for the degrees at which emission control measures are applied. More detail is available in Cofala and Syri, 1998a, Cofala and Syri, 1998b, Klimont *et al.*, 2000, Klimont, Zbigniew *et al.*, 2002, Klimont and Brink, 2006, Klaassen *et al.*, 2005, Höglund-Isaksson, Lena and Mechler, Reinhard, 2005a, Winiwarter, 2005, Tohka, 2005b. GAINS estimates future emissions according to Equation 1 by varying the activity levels along exogenous projections of anthropogenic driving forces and by adjusting the implementation rates of emission control measures.

3.2 Emission control measures and their costs

3.2.1 EMISSION CONTROL OPTIONS

Basically, three groups of measures to reduce emissions can be distinguished:

- *Behavioral changes* reduce anthropogenic driving forces that generate pollution. Such changes in human activities can be autonomous (e.g., changes in life styles), they could be fostered by command-and-control approaches (e.g., legal traffic restrictions), or they can be triggered by economic incentives (e.g., pollution taxes, emission trading systems, etc.). The GAINS concept does not internalize such behavioral responses, but reflects such changes through alternative exogenous scenarios of the driving forces.

- *Structural measures* that supply the same level of (energy) services to the consumer but with less polluting activities. This group includes fuel substitution (e.g., switch from coal to natural gas) and energy conservation/energy efficiency improvements. The GAINS model introduces such structural changes as explicit control options.

- A wide range of *technical measures* has been developed to capture emissions at their sources before they enter the atmosphere. Emission reductions achieved through these options neither modify the driving forces of emissions nor change the structural composition of energy systems or agricultural activities. GAINS considers about 1,500 pollutant-specific end-of-pipe measures for reducing SO_2, NO_x, VOC, NH_3 and PM emissions and several hundred options for greenhouse gases and assesses their application potentials and costs.

Any optimal allocation of emission control measures across countries and sectors is crucially influenced by differences in emission control costs across emission sources. It is therefore of utmost importance to systematically identify the factors leading to variations in emission control costs among countries, economic sectors and pollutants. Diversity is caused, i.a., by differences in the structural composition of existing emission sources (e.g., fuel use pattern, fleet composition, etc.), the state of technological development, and the extent to which emission control measures are already applied.

Structural measures considered in GAINS

Table 3.1: Major groups of structural measures to reduce emissions of air pollutants and greenhouse gases considered in GAINS. For more details consult Cofala *et al.*, 2008 and Klaassen *et al.*, 2005.

Sector	Measure
Power plants	• Use of renewables, such as o wind, o solar photo-voltaic, o large hydro power plants, o small hydro power, o geothermal power instead of fossil fuels. • Gas-fired power plants instead of coal-fired power plants. • Biomass power plants instead of fossil fuel plants. • Combined heat and power (CHP) systems to substitute electric power plants on the one hand, and either industrial boilers or residential boilers. CHP increase the overall energy system efficiency. • (Efficiency measures that reduce electricity consumption in industry and the residential/commercial sector that reduce electricity consumption)
Residential sector	• Energy saving packages (3 stages each) for heating, cooling, air conditioning for o existing houses, o new houses, o existing apartments, o new apartments. • Energy saving packages (3 stages each) for o water heating, o cooking, o lighting, o small appliances, o large appliances.
Commercial sector	• Energy saving packages (3 stages each) for heating, cooling, air conditioning for o existing buildings, o new buildings. • Energy saving packages (3 stages each) for o water heating o cooking, o lighting, o small appliances, o large appliances.
All industries	• Gas-fired boilers instead of coal-fired boilers. • Combined Heat and Power instead of industrial boilers.
Cement production	• Energy saving packages (3 stages)
Iron and steel industry	• Energy saving packages (3 stages)
Paper and pulp industry	• Energy saving packages (3 stages)
Non-ferrous metals	• Energy saving packages (3 stages)
Chemicals	• Energy saving packages (3 stages)
All transport	• Substitute fossil fuel with bio-fuels

Technical emission control measures considered in GAINS

Table 3.2: Major groups of technical measures to reduce emissions of CO_2 considered in GAINS. For more details consult Klaassen *et al.*, 2005.

Sector	Measure
Power plants	• IGCC (Integrated Gasification Combined Cycle) instead of conventional coal fired power plants • Carbon capture and storage
Passenger cars	• Advanced internal combustion engines • Hybrid vehicles • Plug-in hybrids • Electric vehicles • Hydrogen fuel-cell vehicle • Non-traction related efficiency improvements
Light-duty trucks	• Advanced internal combustion engines • Hybrid vehicles • Plug-in hybrids • Electric vehicles • Hydrogen fuel-cell vehicles • Non-traction related efficiency improvements
Heavy-duty trucks	• Advanced internal combustion engine • Non-traction related efficiency improvements
Buses	• Electric vehicle • Hydrogen fuel-cell vehicle • Non-traction related efficiency improvements (2 stages)
Motorcycles	• Advanced internal combustion engine

Table 3.3: Major groups of control measures for SO_2 emissions considered in GAINS. For more details consult Cofala and Syri, 1998a

SO_2	
Stationary combustion sources	▪ Low sulphur fuels (coal and heavy fuel oil with max. 0.6 %S, low S medium distillates (0.2 and 0.05 %S) ▪ In-furnace controls (limestone injection) ▪ Flue gas desulphurization (with various removal efficiencies)
Industrial processes	▪ Three generic reduction stages
Mobile sources	▪ Low sulphur heavy fuel oil (0.5 %S), and low S medium distillates (0.2 and 0.05 %S) ▪ Sulfur free (10 ppm) gasoline and diesel oil

Table 3.4: Major groups of control measures for NO_x emissions considered in GAINS. More details are available in Cofala and Syri, 1998b

NO_x	
Stationary combustion sources	▪ Combustion modifications (combination of low NO_x burners, overfire air, staged combustion techniques etc.) ▪ Selective non-catalytic reduction (SNCR) on medium-size industrial boilers ▪ Selective catalytic reduction (SCR) on larger boilers
Industrial processes	▪ Three generic reduction stages
Mobile sources	▪ Emission standards on motorcycles and mopeds (Stage I to Stage III) ▪ Standards on cars and other light-duty road vehicles (Euro 1 to Euro 6) ▪ Standards on buses and heavy-duty trucks (Euro I to Euro IV) ▪ Standards on mobile non-road internal combustion engines, including shipping sector (several source-specific stages)

Table 3.5: Major groups of control measures for PM emissions considered in GAINS. More details are available in Klimont, Z. *et al.*, 2002

PM	
Stationary combustion and process sources	▪ Low efficiency measures (cyclones) ▪ Medium efficiency measures (one-stage electrostatic precipitators) ▪ High efficiency dedusters (multi-stage electrostatic precipitators, bag filters) ▪ Good housekeeping measures (e.g., improved maintenance)
Domestic combustion	▪ Improved (low emission) stoves ▪ Advanced design new stoves and boilers (e.g., pellet stoves) ▪ Good housekeeping measures (e.g., improved maintenance)
Mobile sources	▪ Emission standards (as for NO_x)
Agriculture	▪ Ban on open burning of agricultural residues

Table 3.6: Major groups of control measures for NH_3 emissions considered in GAINS. More details are available in Klimont and Brink, 2004

NH_3	
Livestock breeding	▪ Modified feeding strategies; dietary changes for cattle, pigs and poultry ▪ Low emission housing ▪ Covered outdoor storage of manures ▪ Low emission application of manures onto soils (e.g., immediate plowing, slurry injection)
Mineral fertilizer application	▪ Substitution of ammonium nitrate for urea or ammonium bicarbonate

Table 3.7: Major groups of control measures for VOC emissions considered in GAINS. More details are available in Klimont *et al.*, 2000

VOC	
Domestic combustion	▪ Measures as for PM reduction
Production and distribution of liquid and gaseous fuels	▪ Floating covers and double seals on storage tanks ▪ Leak detection and management programs ▪ Vapour capture and recovery at terminals, depots, and service stations ▪ Improved flaring efficiency
Solvent use	▪ Primary measures aiming at reducing losses and improving solvent recovery rates (e.g., solvent management plans) ▪ Primary measures; process modification ▪ Low solvent, high solid, powder, and water based paints ▪ End-of-pipe options including primarily adsorption and incineration units
Mobile sources	▪ Emission standards (as for NO_x) including carbon canisters in all EURO stages for gasoline engines
Agriculture	▪ Ban on open burning of agricultural residues

Table 3.8: Major groups of control measures for CH_4 emissions considered in GAINS. More details are available in Höglund-Isaksson *et al.*, 2008 and Höglund-Isaksson, L. and Mechler, R., 2005

CH_4	
Agriculture	• Anaerobic digestion of animal manure • Dietary changes for dairy cows and cattle • Alternative rice strains and improved aeration of rice fields • Ban on agricultural waste burning
Waste	• Waste diversion options: recycling of paper and wood waste, composting and bio-gasification of food waste, and waste incineration • Landfill options: gas recovery with flaring or gas utilization
Wastewater	• Domestic urban wastewater collection with aerobic or anaerobic treatment with or without gas recovery • Domestic rural wastewater treatment in latrines or septic tanks. • Industrial wastewater treatment –aerobic or anaerobic with or without gas recovery utilization
Coal mining	• Recovery with flaring or utilization of gas
Gas distribution	• Replacement of grey cast iron networks and increased network control frequency
Natural gas and oil production and processing	• Recovery and flaring of gas

Table 3.9: Major groups of control measures for N_2O emissions considered in GAINS. More details are available in Höglund-Isaksson *et al.*, 2008 and Winiwarter, 2005

N_2O	
Agriculture	• Reduced and/or improved timing of fertilizer application • Use of advanced agro-chemicals (e.g., nitrification inhibitors) • Precision farming
Energy combustion	• Combustion modifications in fluidized bed boilers
Industrial processes	• Catalytic reduction in nitric and adipic acid production
Waste water	• Optimization of operating conditions in wastewater plants
Direct N_2O use	• Replacement/reduction in use of N_2O for anaesthetic purposes

Table 3.10: Major groups of control measures for F-gas emissions considered in GAINS. More details are available in Höglund-Isaksson *et al.*, 2008 and Tohka, 2005a

F-gases		
HFC	Aerosols	▪ Alternative propellant
HFC	Stationary air conditioning and refrigeration	▪ Good practice: leakage control, improved components, and end-of-life recollection ▪ Process modifications for commercial and industrial refrigeration
HFC	Mobile air conditioning and refrigeration	▪ Alternative refrigerant: pressurized CO_2 ▪ Good practice: leakage control, improved components, and end-of-life recollection
HFC	HCFC-22 production	▪ Incineration: post combustion of HFC-23
HFC	Foams	▪ Alternative blowing agents
HFC	Aerosols	▪ Alternative propellant
PFC	Primary aluminium production	▪ Conversion of SWPB or VSS to PFPB ▪ VSS and SWPB retrofitting
PFC	Semiconductor Industry	▪ Alternative solvent use: NF_3
SF_6	Magnesium production and casting	▪ Alternative protection gas SO_2
SF_6	High and mid voltage switches	▪ Good practice: leakage control, improved components, and end-of-life recollection
SF_6	Other SF_6 use	▪ Ban of SF_6 use

3.2.2 ESTIMATES OF EMISSION CONTROL COSTS

The GAINS model calculates for each country and mitigation option the costs taking into account technology- and country-specific circumstances. The model attempts to quantify the values to society of the resources diverted to reduce emissions. In practice, these values are approximated by estimating costs at the production level rather than at the level of consumer prices. Therefore, any mark-ups charged over production costs by manufacturers or dealers do not represent actual resource use and are ignored. Any taxes added to production costs are similarly ignored as subsidies as they are transfers and not resource costs. All costs are given in Euros at the 2005 price level.

Unit costs of emission reductions achieved with a given measure

A central assumption in the GAINS cost calculation is the existence of a free market for (abatement) equipment throughout Europe that is accessible to all countries at the same conditions. Thus, the capital investments for a certain technology can be specified as being independent of the country. Simultaneously, the calculation routine takes into account several country-specific parameters that characterise the situation in a given region e.g., labour costs and emission factors. Expenditures for emission controls are differentiated into:

- investments,
- operating and maintenance costs, and
- cost savings.

For each of the 1,500 emission control options, GAINS estimates their costs of local application considering annualized investments (I^{an}), fixed (OM^{fix}) and variable (OM^{var}) operating costs, and how they depend on technology *m*, country *i* and activity type *k*. Unit costs of abatement (*ca*), related to one unit of activity (*A*), add up to:

$$ca_{i,k,m} = \frac{I^{an}_{i,k,m} + OM^{fix}_{i,k,m}}{A_{i,k}} + OM^{var}_{i,k,m}\,. \qquad (2)$$

Depending on the purpose of the cost calculation, control costs can be expressed in relation to the achieved emission reductions. Such unit costs are useful for cost-effectiveness analysis, as long as a single pollutant is considered. In such a case costs per unit of abated emissions (*cn*) of a pollutant p are calculated as:

$$cn_{i,k,m,p} = \frac{ca_{i,k,m}}{ef_{i,k,0,p} - ef_{i,k,m,p}} \qquad (3)$$

where $ef_{i,k,0,p}$ is the uncontrolled emission factor in absence of any emission control measure (m=0). Such coefficients are also useful for constructing cost curves of emission reductions for a single pollutant, as long as they to not account for interactions with and side-impacts on other pollutants.

In order to avoid arbitrary allocations of costs across several pollutants, the multi-pollutant optimization of the GAINS model compares the cumulative effects on all affected pollutants and compares them with the total costs of the measure (per activity) as specified in Equation 2.

Details on cost calculation methodologies for the different pollutants that are considered in GAINS are provided in separate reports listed in Table 3.11. Note that actual input data to cost calculations can be extracted from the GAINS-online implementation at the Internet (http://gains.iiasa.ac.at).

Table 3.11: References to detailed documentation of the methodologies for describing emission control potentials and costs

Pollutant	Reference
SO_2	Cofala and Syri, 1998a
NO_x	Cofala and Syri, 1998b
PM	Klimont, Z. *et al.*, 2002
NH_3	Klimont and Brink, 2004
VOC	Klimont *et al.*, 2000
CO_2	Klaassen *et al.*, 2005
CH_4	Höglund-Isaksson *et al.*, 2008, Höglund-Isaksson, Lena and Mechler, Reinhard, 2005b
N_2O	Höglund-Isaksson *et al.*, 2008, Winiwarter, 2005
F-gases	Höglund-Isaksson *et al.*, 2008, Tohka, 2005b

3.2.3 THE USE OF COST DATA IN GAINS

In contrast to the single-pollutant cost curve approach that has been used in the RAINS model, the optimization module of GAINS uses an explicit representation of technologies. While in RAINS the decision variables in the cost optimization are the segments of (independent) cost curves based on a fixed energy projection, in GAINS the decision variables are the activity levels of individual technologies themselves.

The advantages of this approach are fourfold:

- Multi-pollutant technologies are represented adequately in this approach. Multi-pollutant emission control technologies, such as those meeting the various Euro-standards for road vehicles, can be cost-effective in a multi-pollutant multi-objective regulatory framework, even though as single pollutant control technologies they may be not. Thus, while in a cost curve approach multi-pollutant technologies often do not appear to be cost effective, in the GAINS optimization these technologies are appraised on the basis their efficiency to meet (potentially) several environmental objectives simultaneously.
- GAINS allows for (limited) changes in the underlying energy system, primarily as possible measures to reduce greenhouse gas emissions. With each change in the energy system, however, the potential for air pollution control technologies may change, and thus in RAINS the individual cost curve would need to be recalculated for each change in the energy system. Using an explicit technology representation in the GAINS optimization avoids such a cumbersome procedure, as the model "sees" the available technologies and their potentials for their application *at every stage*.
- The GAINS approach fully integrates air pollution control and greenhouse gas mitigation measures so that it not only possible to address the two issues *sequentially*,

as has been done in the past: with this tool both aspects of emission control can be addressed *simultaneously* to increase economic efficiency and environmental effectiveness.

- Emission control costs are directly associated with technologies, rather than with pollutants. For single pollutant technologies this difference is spurious, but both for multi-pollutant technologies and activities changes commonly considered as greenhouse gas mitigation options it is often inappropriate to attribute costs to the reduction of a single pollutant or to allocate the costs to individual pollutants. With the technology approach of GAINS no such allocation is needed, nor is it always possible.

Another important consequence of the technology representation in GAINS is the extension of the concept of maximum technically feasible reductions (MTFR). While in the RAINS approach the point of MTFR on a single pollutant cost curve was determined by the maximum application of end-of-pipe technologies, in GAINS further reductions can be achieved by changing the underlying activities, e.g., the energy mix for a given sub-sector. Thus, for example, a switch from coal to gas or to a renewable fuel will reduce emissions of particles below a level that could be achieved with filter technologies. Though a particular fuel switch may not be cost-effective as a control measure for a single air pollutant, it is important to take this additional potential for reduction into account when air pollution targets are discussed, particularly in a carbon constrained setting.

It is important to take note of the fact that the GAINS optimization module can still be used to construct single pollutant cost curves for individual countries if so desired. In this mode the GAINS model is allowed to use all add-on technologies for air pollution control like in the RAINS model, but fuel substitutions or efficiency improvement options are suppressed, i.e., are not available. Ignoring multi-pollutant technologies for the time being, the GAINS model in RAINS mode exactly reproduces the results of the original RAINS optimization approach.

4 Atmospheric dispersion

The global-regional chemistry transport model TM5 was used to develop source receptor (SR) relationships of aerosol and ozone precursors that describe the response of a range of air quality indicators to changes in the emissions of the various pollutants in each of the source regions.

4.1 Atmospheric source-receptor relationships

4.1.1 APPROACH

Reduced-form source-receptor relationships describe the spatial response of an air quality indicator to changes in precursor emissions in a given source region in a computationally efficient form that can be readily implemented in the GAINS-Asia integrated assessment model. In practice, source-receptor relationships have been derived through a sample of TM5 model experiments with systematic perturbations of emissions for each source regions. The resulting changes in air quality indicators (ambient concentrations of PM and ozone, deposition of sulfur, etc.) over the model domain have been related to the assumed perturbation in emissions in order to derive the response of these indicators to a change of one unit of emissions. In GAINS-Asia, this response is then scaled up by the amount of emission changes that results from an emission control scenario.

Special emphasis has been given to the functional form of source-receptor relationships. Based on similar work for Europe, it has been shown that responses of PM2.5 concentrations to changes in primary PM2.5 emissions can be described by linear relationships. The response of secondary inorganic aerosols can be approximated by piecewise linear functions distinguishing the chemical regimes of the availability of ammonia in the atmosphere. For regional scale ozone concentrations, current levels of NO_x concentrations in Asia suggest the suitability of linear response functions to changes in NO_x and VOC emissions. However, these assumptions need to be confirmed for drastically higher NO_x emissions, and do not necessarily hold for ozone within urban areas.

Furthermore, a health impact assessment requires more spatially detailed information of population exposure in urban areas, where the majority of people live. The standard setup of TM5, however, calculates ambient concentrations of the various pollutants with a 1*1 degree spatial resolution, which are not necessarily representative for concentrations within urban areas. A routine has been developed to identify sub-grid differences in PM concentrations as a function of local emission densities and the spatial extensions of urban areas within a grid cell.

Based on the data sample of scenarios produced with the TM5 models, computationally efficient source-receptor relationships were constructed that describe the response of

- annual mean concentrations of PM2.5 in each 1*1 degree grid cell over Asia to changes in emissions in each of the source regions (Chinese provinces or Indian States) of
  - Primary PM2.5,
  - SO_2,

- o NO_x,
- o NH_3.

This formulation describes the formation of PM from anthropogenic primary PM emissions and secondary inorganic aerosols. It excludes PM from natural sources and primary and secondary organic aerosols due to insufficient confidence in the current modelling ability. Thus, it does not reproduce the full mass of PM2.5 that is observed in ambient air.

- A health-relevant metric of ground-level ozone (SOMO35, i.e., the sum of maximum 8-hour ozone levels over 35 ppb) and a vegetation-damage relevant ozone metric (AOT40) in each 1*1 degree grid cell over Asia to changes in emissions in each of the 32 Chinese provinces of NO_x emissions.

4.1.2 TM5 CALCULATIONS TO DERIVE SOURCE-RECEPTOR RELATIONSHIPS

In order to derive reduced form relationships for ozone, and particulate matter the TM5 model's infrastructure was modified to enable more automated simulations. To speed up the simulations SR relationships simulations were analyzed using 4 "master" regions, in which were embedded the 31 states, and 32 provinces in India and China, respectively.

An example of such a set-up is given in Figure D5.1 for a zoom over Southern Asia.

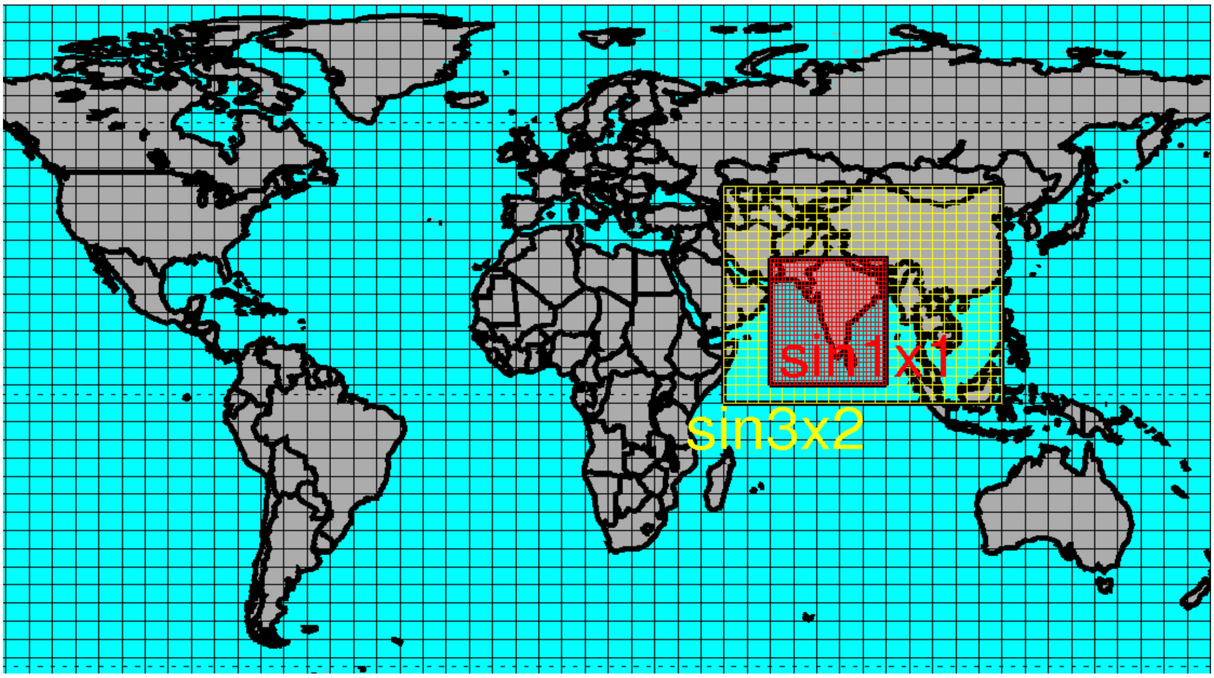


Figure 4.1: An example of implementation of zoom regions in the TM5 model

Table 4.1: The four “master regions” for simulations

Region	Longitude	Latitude
North India	Lon= 66°-102°	Lat= 18°- 34°
South India	Lon = 72°-90°	Lat = 2°-22°
North China	Lon = 75°-140	Lat = 35°-52°
South China	Lon = 80°-125	Lat = 20°-38°

Simulations were performed using an unperturbed simulation (base case) and for perturbed conditions where in each region anthropogenic emissions are reduced by 20%. Note that in this set of simulation NH_3 emissions were not perturbed.

Table 4.2: Simulation set-up

Base case	*Emissions of the year 2000*
SO_2COVOC	20 % reduction of SO_2, CO and VOC emissions
NO_xBCPOM	20 % reduction of NO_x, BC and POM
CH4; natural emissions	2000 values.

The results were obtained using the meteorology of the year 2001; a spin-up time of 6 months for the base simulation and one month (December 2000) for the perturbation simulations starting from the corresponding base simulation have been used.

Each simulation generated the following output on the 6ºx4° global grid and for the 3ºx2° and 1ºx1° zoom regions. Each region/state was attribute one “station” location at the point of maximum emission.

Table 4.3: Input data to the calculations

Filename	Components	Time resolution	Spatial resolution
mmix	All chemical components	monthly	3D
Mix_daily	Aerosol components	daily	3D
Mix_hourly	O_3, NO_2, RN222, Rn222 (1day)	hourly	2D
Stations locations (32/26)	All transported chemical components, T, BLH, P	hourly	1D (8 vertical levels)
O_3budget	PO_3, LO_3, StratO_3, FluxCH_4OH, LossCH_4	monthly	3D
budget_global	Dry deposition, wet deposition (CP, LSP) ; sedimentation, Chemical tendencies.	monthly	2D

The following data were post-processed, organized in data files for South Asia and China separately, and provided to IIASA:

Table 4.4: Output provided by the TM5 calculation

Component	Description	unit
O_3	mol_fraction_O3_in_air	ppbv
SOMO35	the annual sum of the daily maximum of 8 hr running average of ozone vol.mixing ratio (M8hO 3) subtracting 35 ppbv	ppbv day
AOT40_corn	The sum of ozone vol. mixing ratio exceeding 40 ppbv, during daylight and 3 months of growing season	ppbv hour
AOT40_soy	The sum of ozone vol. mixing ratio exceeding 40 ppbv, during daylight and 3 months of growing season	ppbv hour
AOT40_wheat	The sum of ozone vol. mixing ratio exceeding 40 ppbv, during daylight and 3 months of growing season	ppbv hour
AOT40_rice1	The sum of ozone vol. mixing ratio exceeding 40 ppbv, during daylight and 3 months of growing season 1	ppbv hour
AOT40_rice2	The sum of ozone vol. mixing ratio exceeding 40 ppbv, during daylight and 3 months of growing season 2	ppbv hour
AOT40_rice3	The sum of ozone vol. mixing ratio exceeding 40 ppbv, during daylight and 3 months of growing season 3	ppbv hour
Deposition NHx	total_deposition_of_atmospheric_nhx	gN/m2/yr
Deposition NOy	total_deposition_of_atmospheric_noy	gN/m2/yr
Deposition SOx	total_deposition_of_atmospheric_sox	gS/m2/yr
Emission NH3	emission_of_atmospheric_nh3	gN/m2/yr
Emission NOx	emission_of_atmospheric_nox	gN/m2/yr
Emission SOx	emission_of_atmospheric_sox	gS/m2/yr
Emission VOC	emission_of_atmospheric_voc	gC/m2/yr
CO	mol_fraction_CO_in_air	ppbv
NO3_a	mass concentration_aerosol_nitrate_in_air	µg/m3
SO4	mass concentration_aerosol_sulfate_in_air	µg/m3
BC	mass concentration_aerosol_black_carbon_in_air	µg/m3
POM	Mass concentration_aerosol_particulate_organic_material_in_air	µg/m3
H2OPART	mass concentration_aerosol_water_in_air	µg/m3
PM_dry	mass concentration_Particulate_Matter_dry_in_air	µg/m3
PM_wet	mass concentration_Particulate_Matter_wet_in_air	µg/m3
PM_urban	mass concentration_Particulate_Matter_dry_in_air valid for the urban fraction of the gridbox	µg/m3
PM_rural	mass concentration_Particulate_Matter_dry_in_air valid for the rural fraction of the gridbox	µg/m3

4.1.3 SUBGRID PARAMETRIZATION OF URBAN/RURAL BC+POM

In exposure assessment studies it is important to know which fraction of the population is exposed to high concentrations. Since the TM5 model calculations were performed using emissions and a model on a 1°x1° resolution, and urban centres typically have the dimension of <10 to 50 km, a parameterisation was developed that takes sub-grid effects into account. The starting point for this routine was the BC + primary POM (PPOM) concentrations as computed by the full TM5 model. However, the parameterisation can also be applied to other PM2.5/PM10 components.

Without horizontal mixing, the concentration C in a gridbox is given by

$$C = \frac{E}{\lambda} \tag{4}$$

with E = in-cell emission intensity of BC+Primary POM (PPOM)

λ = in-cell mixing rate, as approached by the Radon dilution rate.

The actual concentration in the grid box, as resulting from the full TM5 horizontal transport dynamics, is obviously lower. This TM5 modelled grid box concentration (BC+PPOM) is represented by CTM5.

If we distinguish rural from urban emissions, we can define the (non-horizontally-mixed) rural concentration as

$$C_{RUR} = \frac{E_{RUR}}{\lambda} = \frac{1-f_{up}}{1-f_{ua}}\frac{E}{\lambda} \tag{5}$$

With f_{up} = urban population fraction in the grid cell determined from the CIESIN 2'5x2'5 population database

f_{ua} = urban area fraction in the grid cell

This concentration has to be corrected for the horizontal mixing (see below). After correcting the rural concentration, the urban concentration must fulfil the requirement that:

$$f_{ua}C_{URB} + (1-f_{ua})C_{RUR} = CTM5 \tag{6}$$

The horizontal dilution correction is estimated as follows. We define the <u>difference</u> between C and $CTM5$ as the horizontal mixing <u>bias</u>, and apply this to correct C_{RUR}:

$BIAS = C - CTM5$

$$C_{RUR,corr} = \frac{1-f_{up}}{1-f_{ua}}\frac{E}{\lambda} - BIAS = \frac{1-f_{up}}{1-f_{ua}}\frac{E}{\lambda} - \frac{E}{\lambda} + CTM5 = CTM5 - \frac{E}{\lambda}\left(1 - \frac{1-f_{fup}}{1-f_{ua}}\right) \tag{7}$$

We further introduce the limitation that $C_{RUR,corr}$ should not be lower than 0.5*$CTM5$.

C_{URB} follows then immediately from [3].

We note that the parameterization is currently under further development and comparison with measurements.

4.1.4 SENSITIVITY ANALYSES – LINEARITY TESTS

Ozone

Large scale O3 response to emissions perturbations: linearity

The sensitivity of area averaged ozone to different sizes of anthropogenic NO_x emissions perturbations is given in Figure 4.2. The effect of the emission perturbations on region averaged surface O_3 are near-linear for perturbation ranging from 0.8-2, however outside this range (i.e. for perturbations by 0.2 and 5); the response of O3 becomes non-linear. Note that we show later that the combined effect of NOx and CO-VOC perturbations shows a better linearity.

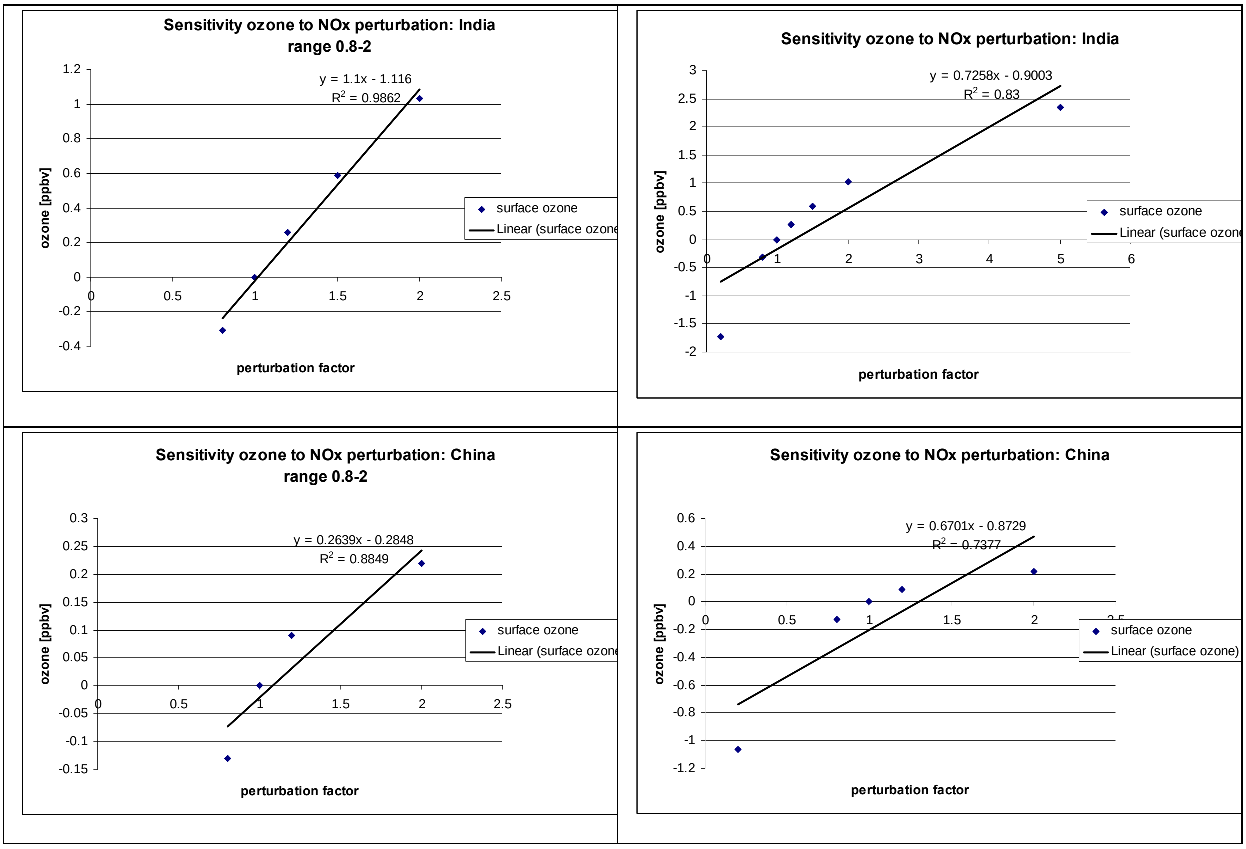


Figure 4.2: Sensitivity of O3 to different size of perturbations. Perturbation steps are 0.2; 0.8, 1.0(no perturbation), 1.5, 2 and 5. The left panels show that for the range 0.8-2.

The plots above were based on the calculations for the South Asia domain (60-110E; and 0-40N) and China. In Figure 4.3 we show that the O_3 response to NO_x perturbations is geographically not homogeneously distributed, but it depends on the balance between O_3 production and titration, clearly visible are the locations of the urban centers.

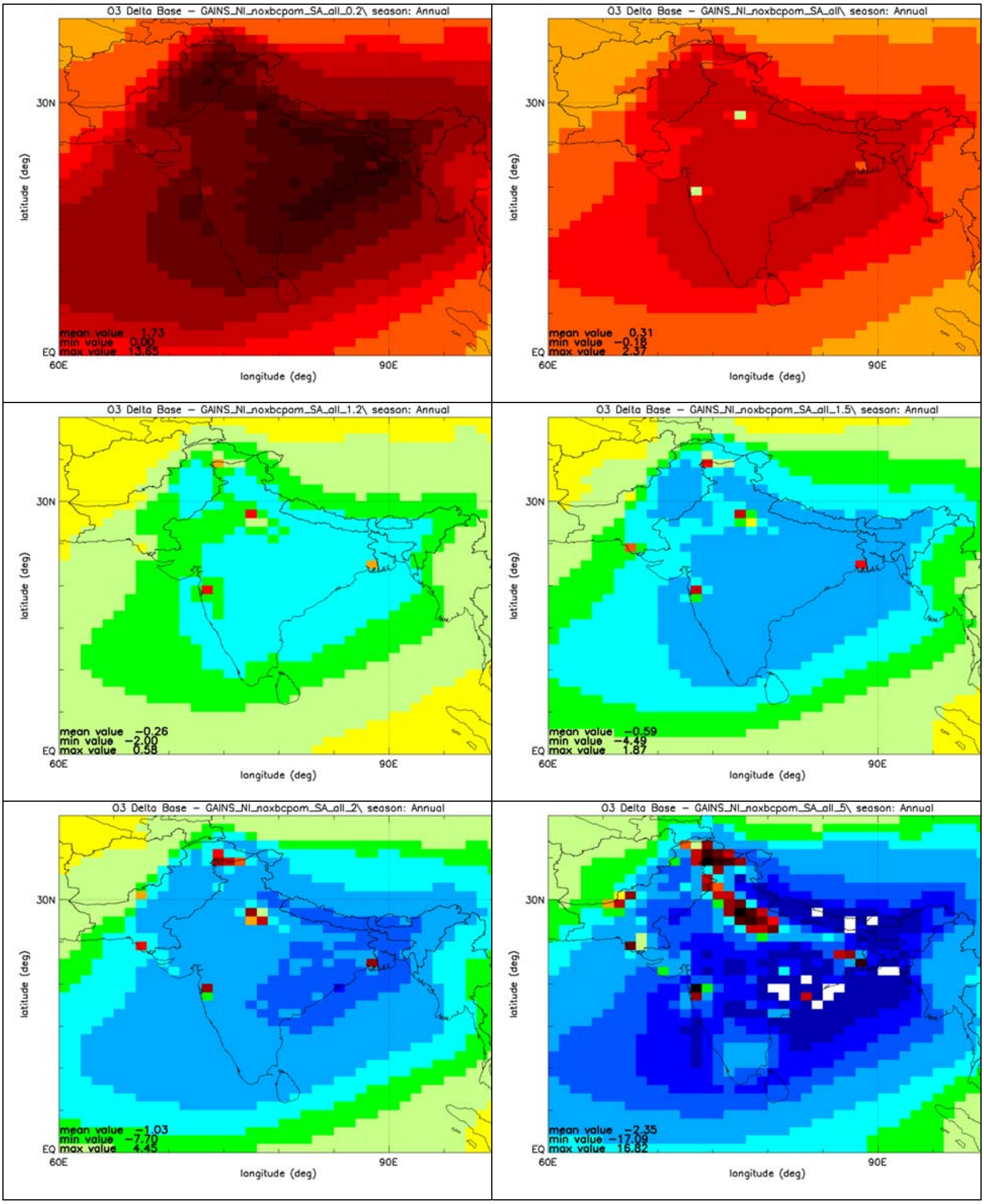


Figure 4.3: The geographical distribution of ozone response to a perturbation of 0.2, 0.8, 1.2, 1.5, 2 and 5 of the anthropogenic NOx emissions

A similar analysis was made for the sensitivity to perturbation of combined effect of perturbing CO and VOC emissions. The large scale O_3 sensitivity is more linear than for NO_x emissions; but a factor of five is pushing is not fully linear anymore. The lower panels show that the perturbations are much more homogeneously distributed over the model domain.

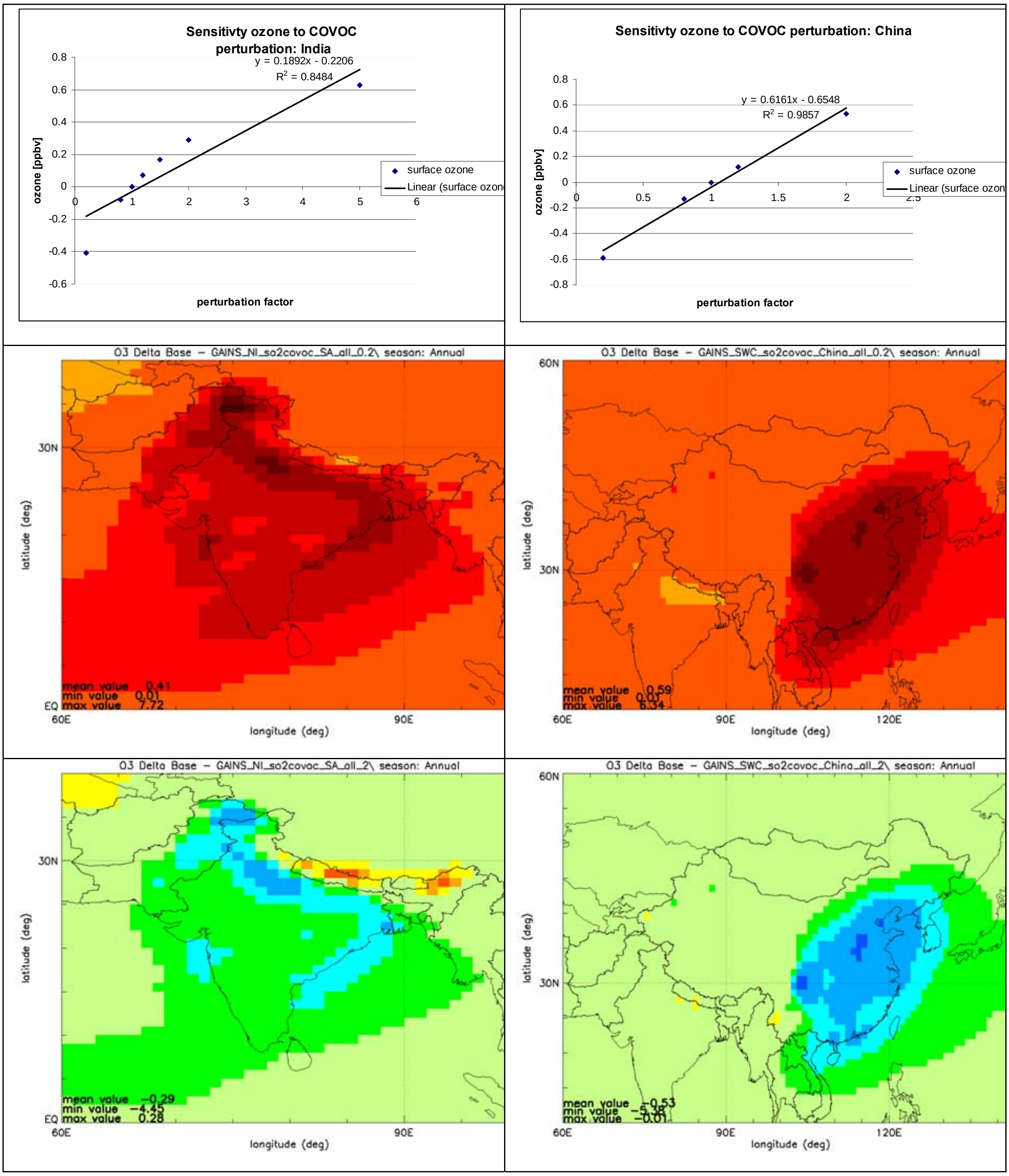


Figure 4.4: Response of O_3 due to CO and VOC emissions

In Figure 4.5 we show the sensitivity of O_3 for the case where NO_x, CO and VOC emissions are simultaneously reduced or increased. The non-linearity induced by changing NO_x emissions alone almost completely disappears; indicating that the chemical regime remains the same over the range of perturbations (i.e., NO_x limited).

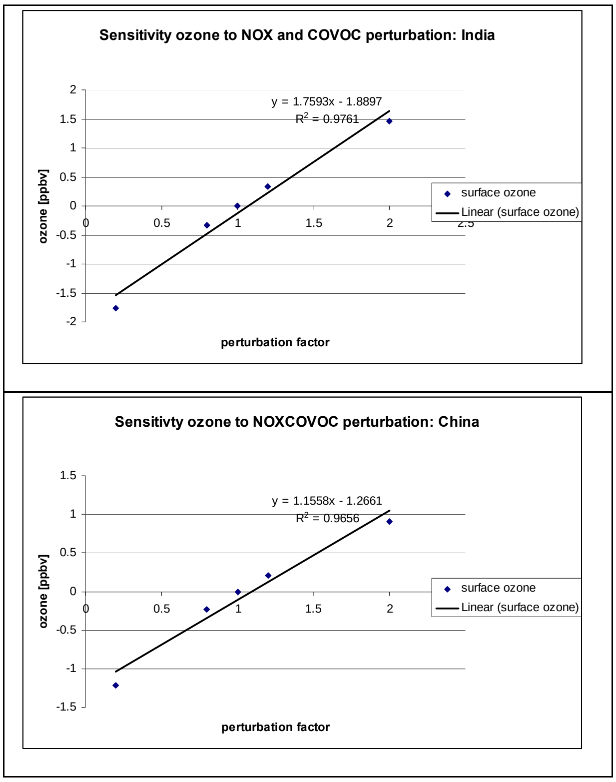


Figure 4.5: Sensitivity to combined NOx and COVOC perturbations

Additivity of single simulations in comparison with perturbation of O_3 for whole region

In this section we evaluate whether the magnitude of the response of O_3 to the sum of perturbations in individual regions is equal to perturbation of all emissions in all regions together. These calculations are based on perturbations by 0.8 of the anthropogenic emissions. The calculations were only performed for the perturbations of noxbcpom (Figure 4.6) and so2covoc (Figure 4.7).

Figure 4.6 shows in general very similar perturbation patters. However, some deviations from additivity in the Southern part of India: this is probably due to numerical effects (here in the 'perturbation of sum' simulation only 1°x1° was used. Some further deviations are seen around the Kolkata region: this needs to be further explored. The non-linear effects over Eastern China are somewhat larger in the order of 10-20%; again this is a numerical effect related of the grid resolution of the SWC zoom regions.

In Figure 4.7 we see that the non-additivity of the simulations is small (except Eastern China due to the resolution effect).

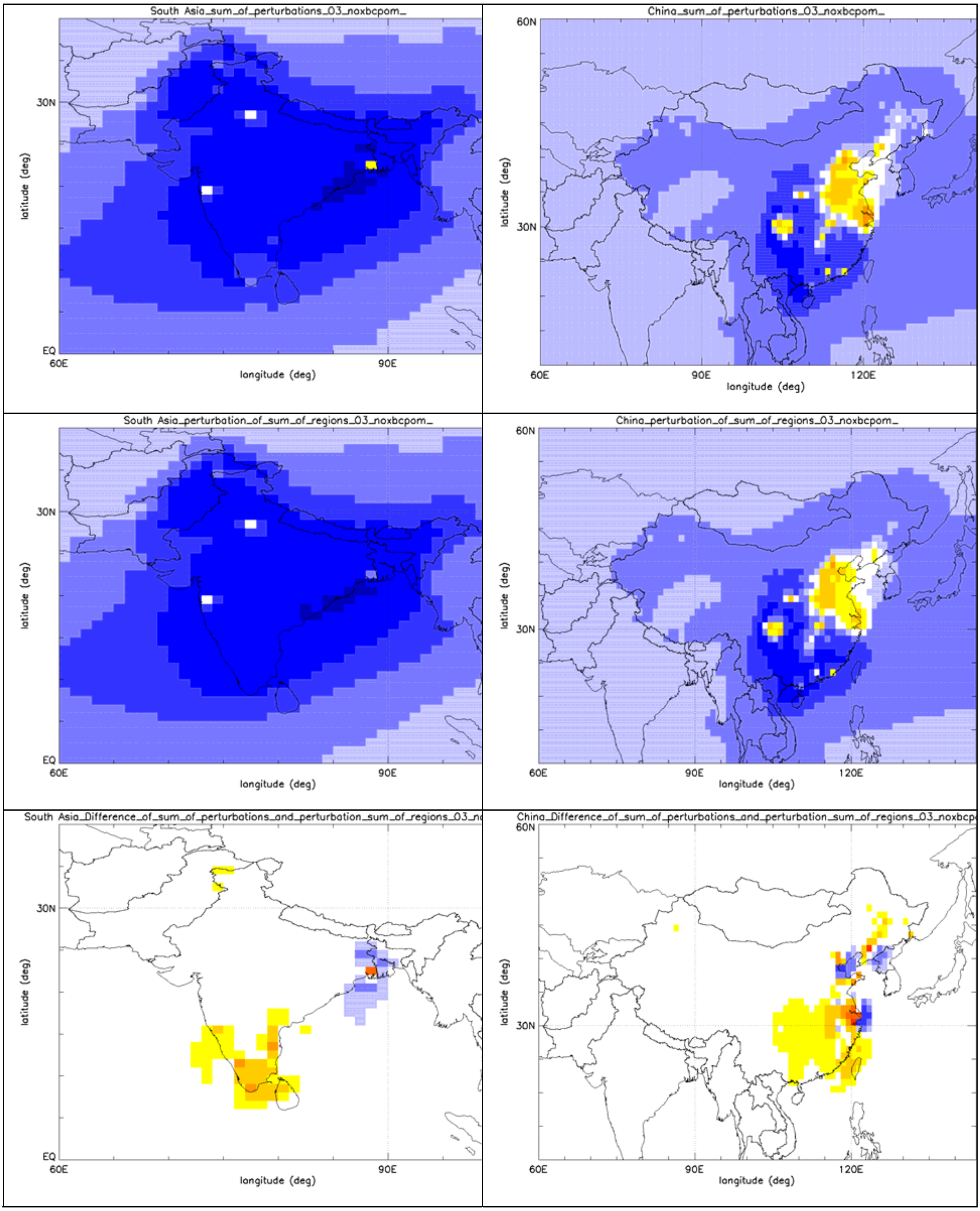


Figure 4.6: Additivity of NOxBCPOM simulations

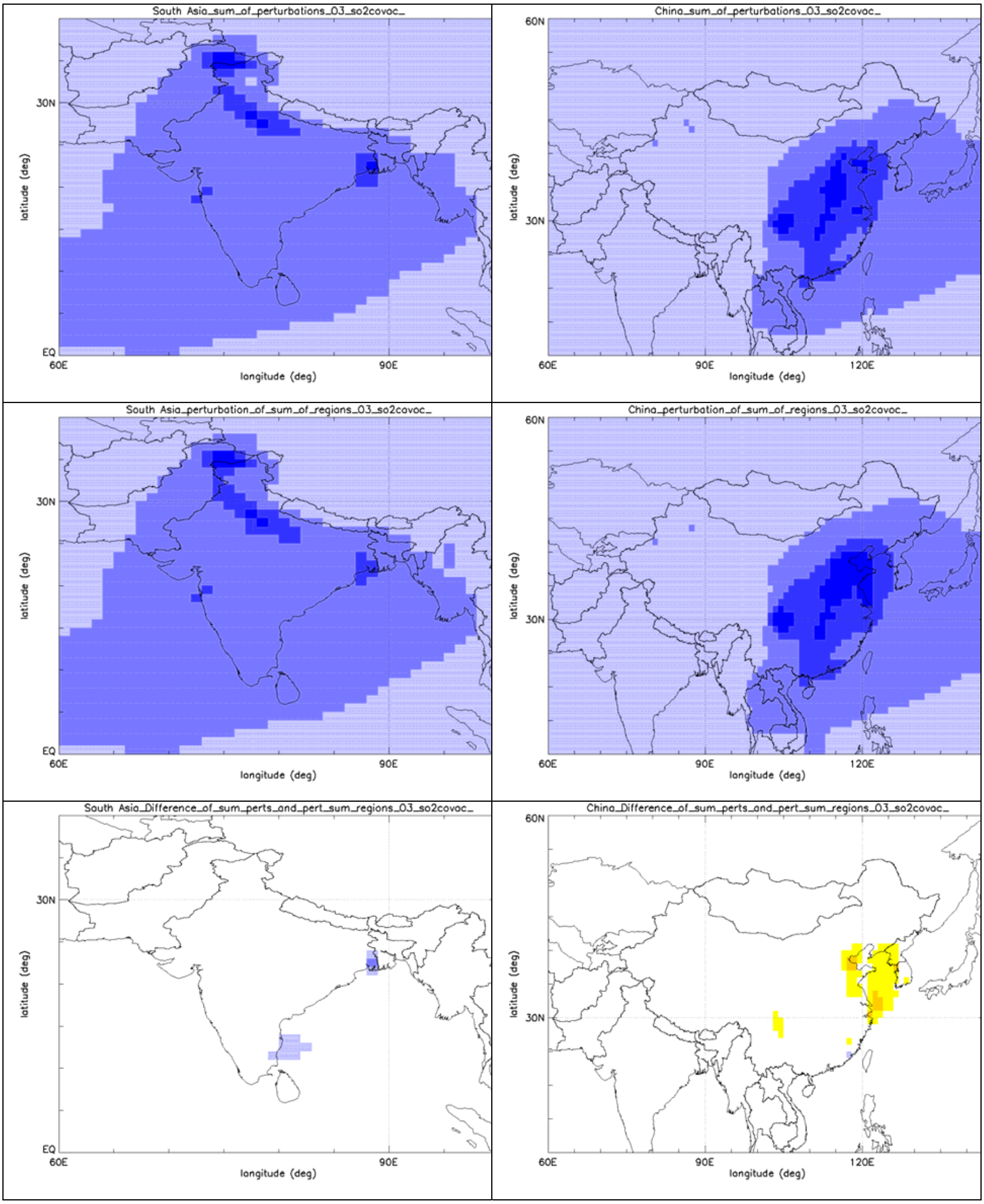


Figure 4.7: Additivity of SO2COVOC simulations

Sensitivity of PM to perturbation

The sensitivity of area averaged PM_wet concentrations to different sizes of anthropogenic BCPOM, SO_2 and all emissions perturbations are given in Figure 4.8. A good overall linearity is found for all cases in South Asia and China.

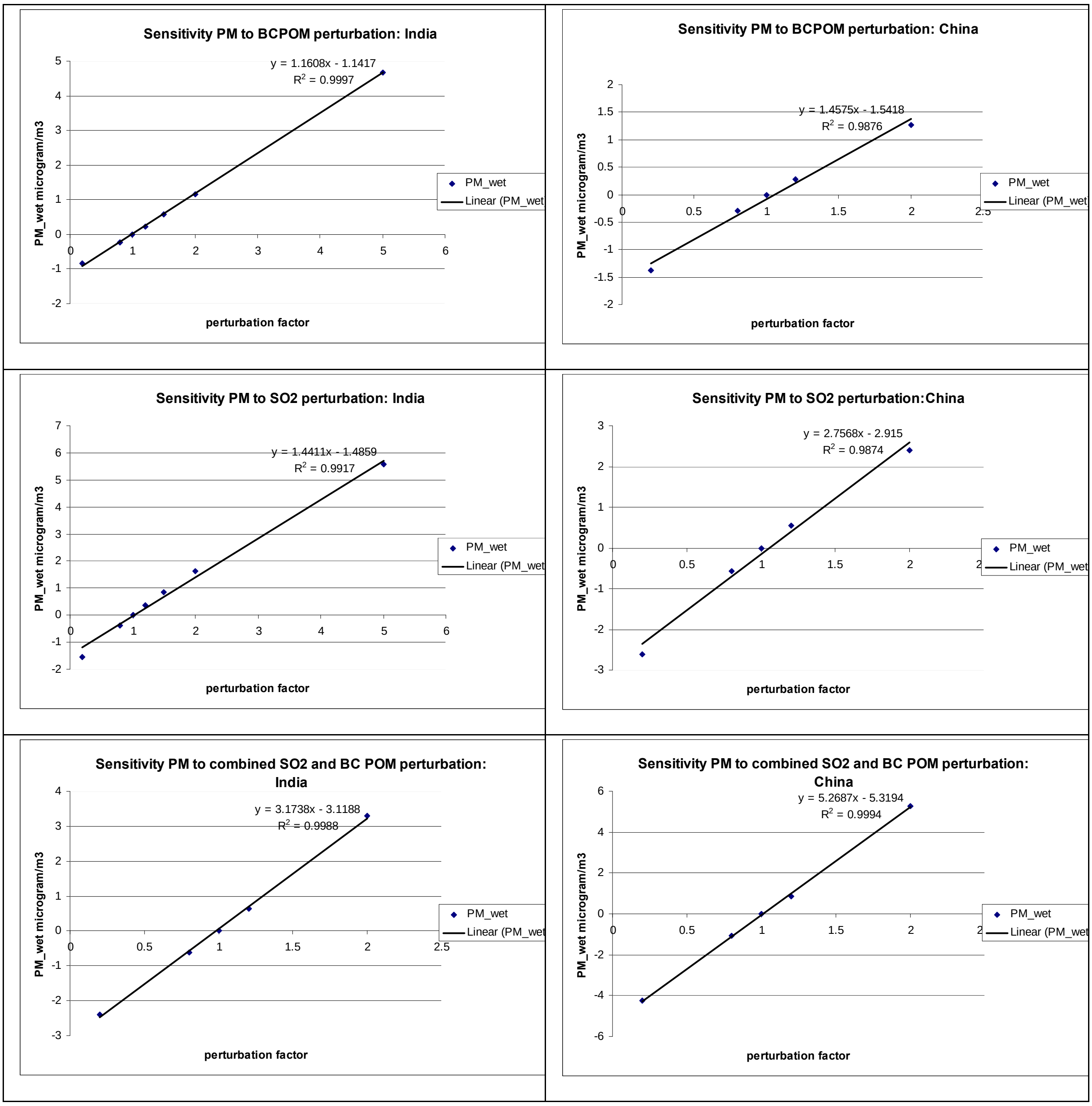


Figure 4.8: Linearity of PM responses to perturbations

Additivity of single simulations in comparison with an overall perturbation PM

In this section we evaluate the extent to which the response of PM to the sum of perturbations in individual regions is equal to perturbation of all emissions in all regions together. These calculations are based on perturbations by 0.8 of the anthropogenic emissions. The calculations were only performed for the perturbations of noxbcpom (not shown) and so2covoc (Figure 4.9).

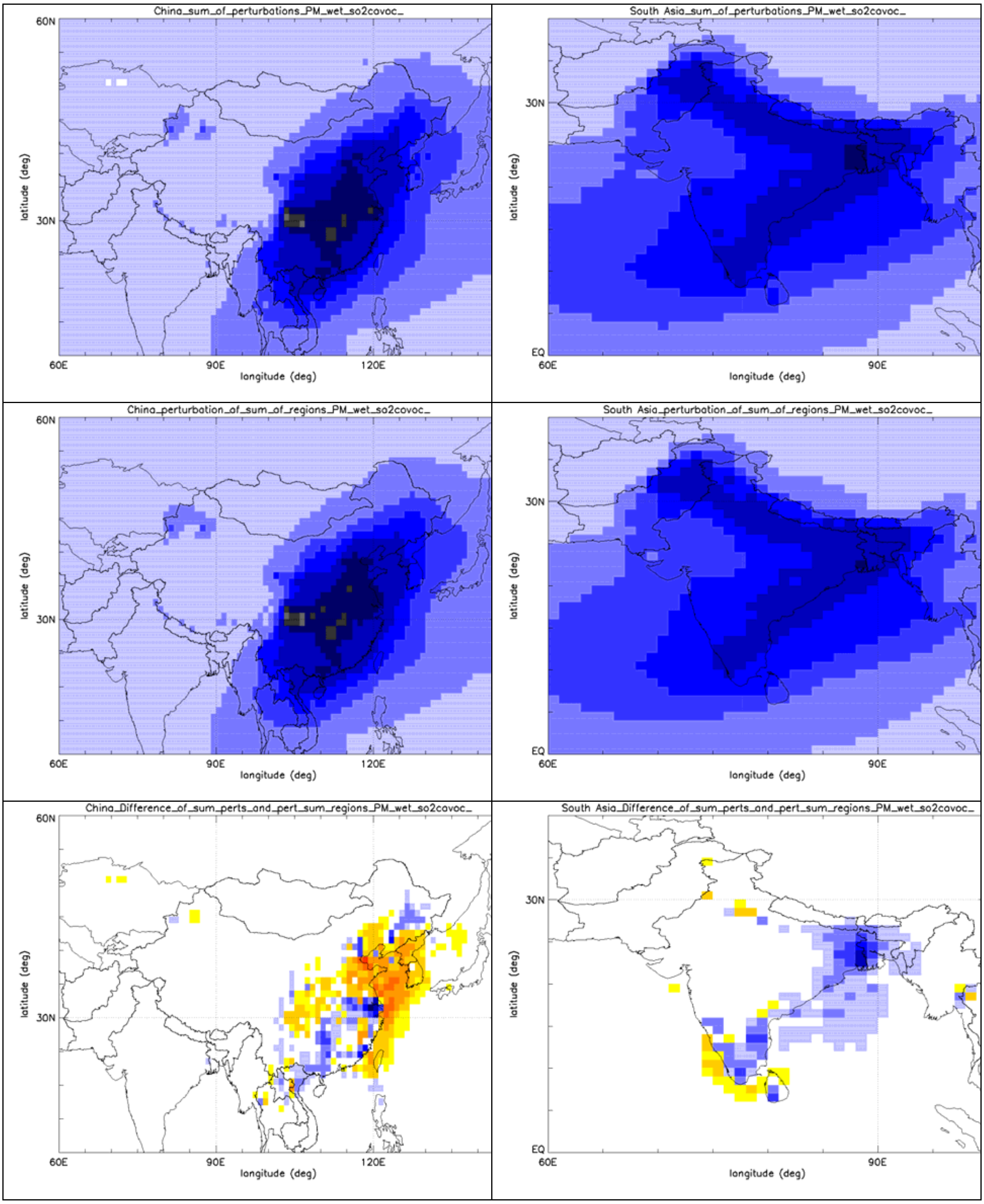
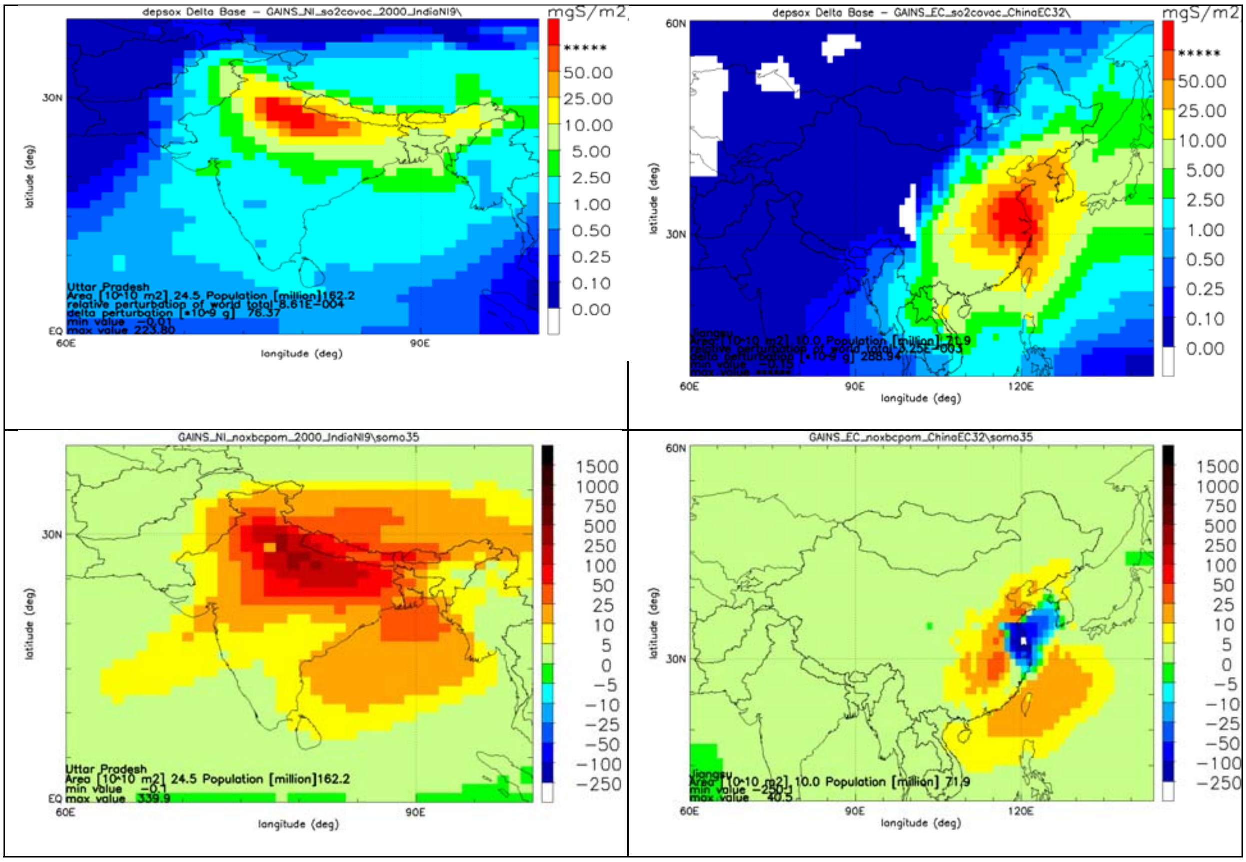


Figure 4.9: Linearity of simulations for perturbation of SO_2 emissions per region

4.1.5 EXAMPLES OF SOURCE-RECEPTOR RELATIONS

In Figure 4.10 we give an example for source receptor relationships for Uttar Pradesh, India, and Jiangsu, China regarding deposition of oxidized sulfur (SOx); SOMO35 (integral of ozone concentrations above 35 ppbv) and PM2.5 (not considering water, and natural aerosol). For presentation reasons the results from a negative perturbation are given as a positive response. Comparison with Figure 4.10 shows the role of transport going from emission to atmospheric concentration, which is clearly different for various gases and aerosol considered. Interestingly, reduction of NO_x emissions in some part of China, may lead to an increase in O_3 (and SOMO35) due to the levels of NO_x already present (*titration effect*). This titration effect may be a serious limitation to the use of linearized SR relationships to estimate effects of emission reductions/increases on ozone.



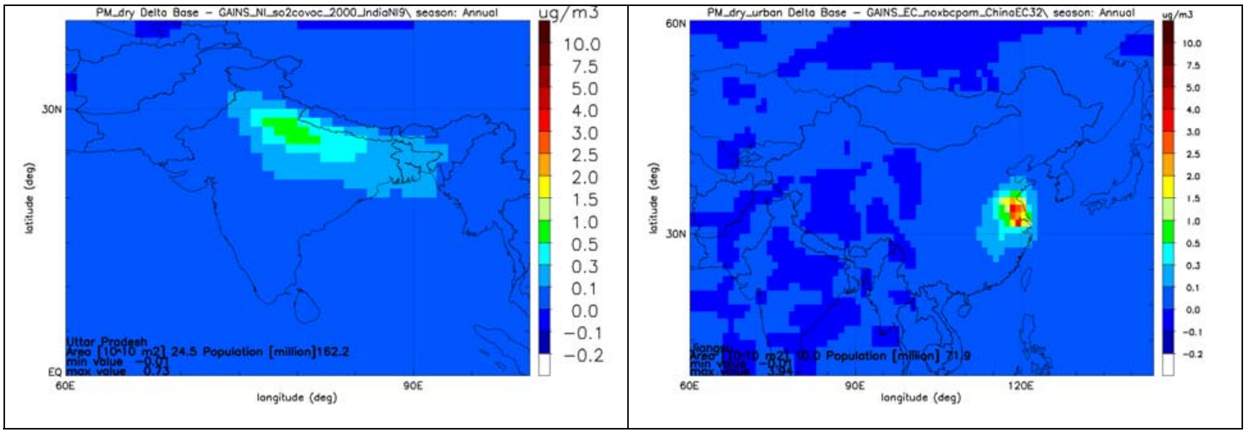


Figure 4.10: Effect of a 20% reduction in the anthropogenic emissions of anthropogenic SO_2 emissions on deposited sulphur (upper row), and of NO_x emissions on SOMO35 (middle row) and primary POM/BC emissions on PM2.5 (lower row) for Uttar Pradesh, India (left column).

Further results are available on http://ccupeople.jrc.it/dentener/results_GAINS.htm, numerical datasets have been transferred to IIASA.

4.1.6 VALIDATION

There is a clear need to assess the validity of the relatively simple $PM_{2.5}$ transfer coefficients derived from model experiments carried out with the TM5 model. In the present case the coefficients were calculated from the results of scenarios in which emissions were modified (by 20%) from those of a single base case using a single set of meteorological conditions. The extent to which such transfer coefficients are applicable to other meteorological situations or different chemical regimes in the atmosphere can be indicated only through validation checks.

Two types of check are routinely performed for GAINS transfer coefficients:

- Comparison of GAINS estimates with the results of the full model for an emissions scenario other than that used in deriving the transfer coefficients;
- Comparison of GAINS calculations with measurements.

The second type of validation check provides an assessment of the entire modelling system, including uncertainties in the full model as well as discrepancies inherent in the simple transfer coefficients, but depends on the availability of sufficient quality-assured measurements covering the range of values found in the area for which the reduced form model will be employed.

Published measurements of $PM_{2.5}$ concentrations in both India and China are relatively scarce, usually restricted to a small number of city locations, and often carried out for specific short-term campaigns rather than covering a full year. In order to assess the applicability of the GAINS transfer coefficients over a wider geographical area than would be possible with $PM_{2.5}$ measurements alone, the validation is first performed against measurements of suspended particulate matter, which have been made at a greater number of sites and over a longer time period. Subsequently, the $PM_{2.5}$ comparison is also presented in the following sections.

India

Comparison with respirable suspended particulate matter

Annual average measurements of respirable suspended particulate matter (RSPM) were extracted from the web page of the Central Pollution Control Board, Ministry of Environment and Forests, India: http://www.cpcb.nic.in/Air_quality_data.php

Data are available for the period 2004 – 2006; measurements for the last two years of this period were used in the comparison with GAINS estimates.

The comparison is shown in Figure 4.11, in which the GAINS estimate for the relevant 1° x 1° grid cell is plotted against the average RSPM measurement of the two years for given Indian cities. For this purpose, the GAINS value is taken as the basic average anthropogenic PM2.5 concentration for the grid cell plus the calculated urban increment – if relevant – plus an estimate of the natural dust concentration taken from the output of the TM5 model.

In view of the many uncertainties involved, the overall level of agreement is reasonable, although it is clear that GAINS tends to underestimate the PM measurements, particularly at higher concentrations. This is likely to be due to greater amounts of dust recorded in the measurements, which are difficult to model with reasonable accuracy, especially in view of their high variability from year to year.

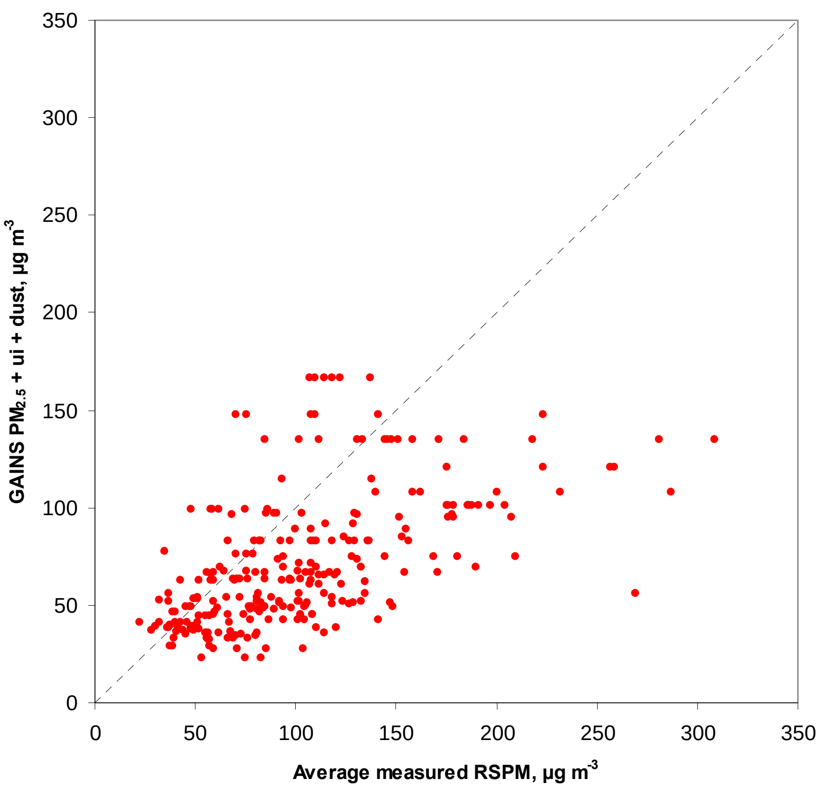


Figure 4.11: Comparison of GAINS estimates of PM2.5 + urban increment + dust with measurements of respirable suspended particulate matter in Indian cities for the period

2004 - 2005.

Comparison with PM2.5 measurements

For the comparison with annual average $PM_{2.5}$ concentrations estimated using the GAINS model, measurements made in the following cities were used: Delhi ESMAP, 2004, Mumbai ESMAP, 2004, Kumar and Joseph, 2006, Kolkota ESMAP, 2004, Chandigarh ESMAP, 2004, Chennai Kim Oanh *et al.*, 2006, Kanpur Sharma and Maloo, 2005 and Lucknow Barman *et al.*, 2008.

The model-measurement comparison is shown in Figure 4.12. The GAINS modelled estimate represented here includes not only the average anthropogenic $PM_{2.5}$ concentration for the relevant grid cell but also the calculated urban increment – if appropriate – plus an estimate of the fine fraction of the natural dust concentration. This was taken to be 30% of the total dust concentration provided by the TM5 model.

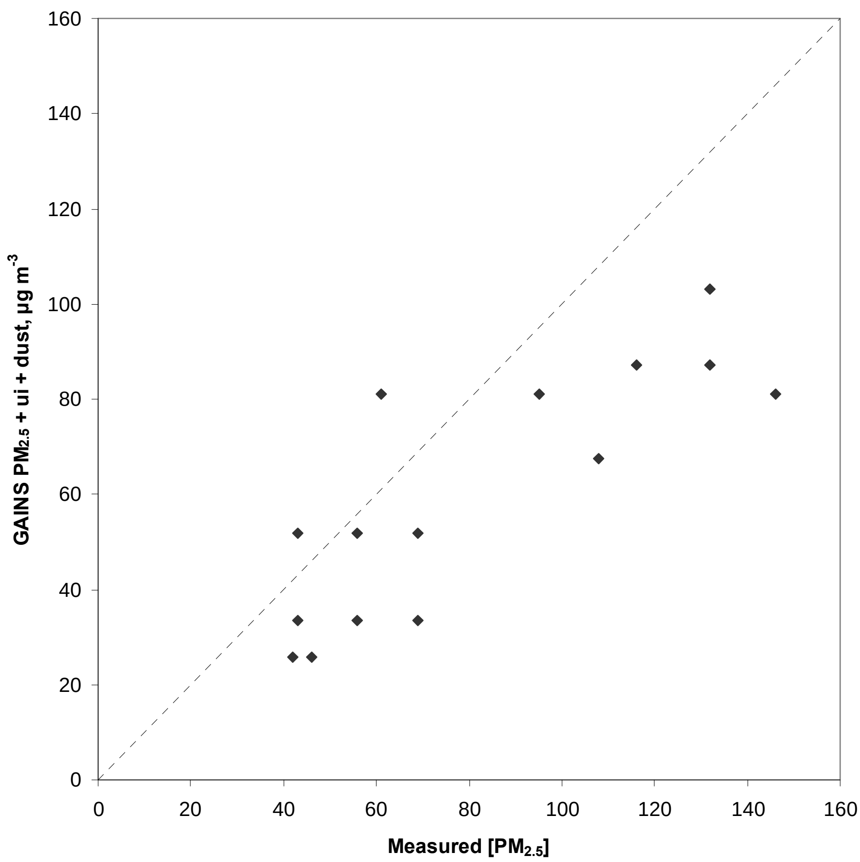


Figure 4.12: Comparison of GAINS estimates of $PM_{2.5}$ + urban increment + fine dust with available PM2.5 measurements in Indian cities.

As is seen from Figure 4.12 there are rather few points on which to base a confident assessment of the GAINS transfer coefficients for India. Indeed, several groups of measurement data reflect the spread in values between different measurement stations in the same city or between different time periods for the same location. In view of this variability in the measurements, the general level of agreement can be considered as encouraging. It is also apparent from Figure 4.12, however, that the GAINS model has a tendency to underestimate the measurements. The reasons for this are not clear.

China

Comparison with PM10 measurements

Annual average PM_{10} measurements were extracted from the web page of the Institute of Public and Environmental Affairs, China (http://air.ipe.org.cn/en/qyInfoEn.do).

Data were available for some 110 cities for all or part of the period 2004 – 2007. The comparison shown in Figure 4.13 uses measurements for 2005 to provide the best temporal match with the emissions estimates underlying the GAINS calculations of PM concentration. There are some indications, however, that better agreement can be obtained by basing the comparison on the average of the four years' measurements, which would tend to reduce the meteorological variability between the measurement years and the year for which the TM5 model was run (used in deriving the GAINS transfer coefficients).

For the comparison in Figure 4.13 the GAINS estimate for the relevant 1° x 1° grid cell is taken as the basic average anthropogenic $PM_{2.5}$ concentration for the grid cell plus an estimate of the natural dust concentration taken from the output of the TM5 model.

The results clearly show considerable scatter but, as with the corresponding validation for India, the general level of agreement is reasonable when the many uncertainties involved, in both the measurements and the modelled estimates, are considered. The large scatter is likely to be due to cities where the natural dust component makes up a relatively large proportion of the PM_{10} total. This dust component is very difficult to model accurately, particularly in view of its high variability from year to year. Indeed, if cities with the higher dust concentrations are removed from the comparison plot, the correlation between model values and measurements is improved (not shown).

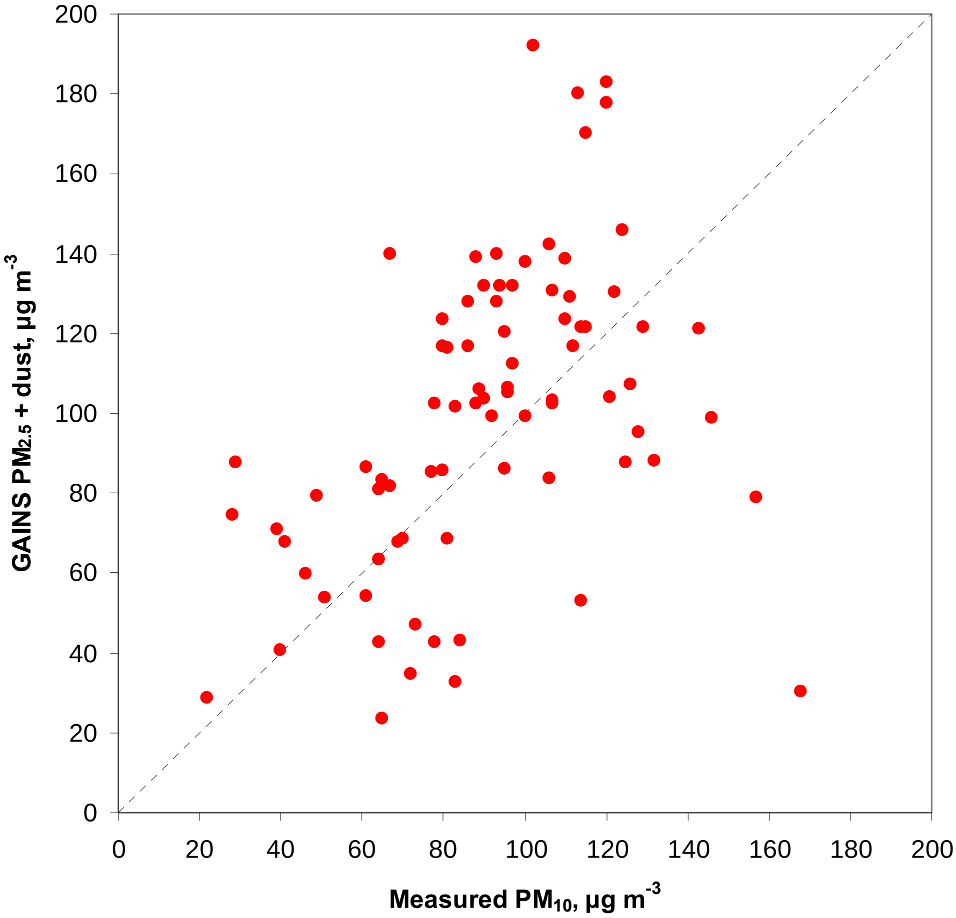


Figure 4.13: Comparison of GAINS estimates of $PM_{2.5}$ + dust with measurements of PM_{10} in Chinese cities for 2005.

Comparison with PM2.5 measurements

A useful overview of reported PM measurements in China is provided by Chan and Yao, 2008. For the comparison with annual average $PM_{2.5}$ concentrations estimated using the GAINS transfer coefficients, measurements made in the following cities were used: Beijing He *et al.*, 2001, Duan *et al.*, 2006, Kim Oanh *et al.*, 2006, Zheng, 2005, Shanghai Ye *et al.*, 2003, Wang *et al.*, 2005, Hong Kong Louie *et al.*, 2005, Chongqing Qian *et al.*, 2001, Guangzhou Qian *et al.*, 2001, Lanzhou Qian *et al.*, 2001 and Wuhan Qian *et al.*, 2001.

The model-measurement comparison is shown in Figure 4.14. The GAINS modelled estimate includes the basic average anthropogenic $PM_{2.5}$ concentration for the relevant grid cell plus the calculated urban increment – if appropriate – plus an estimate of the fine fraction of the natural dust concentration. This was taken to be 30% of the total dust concentration provided by the TM5 model.

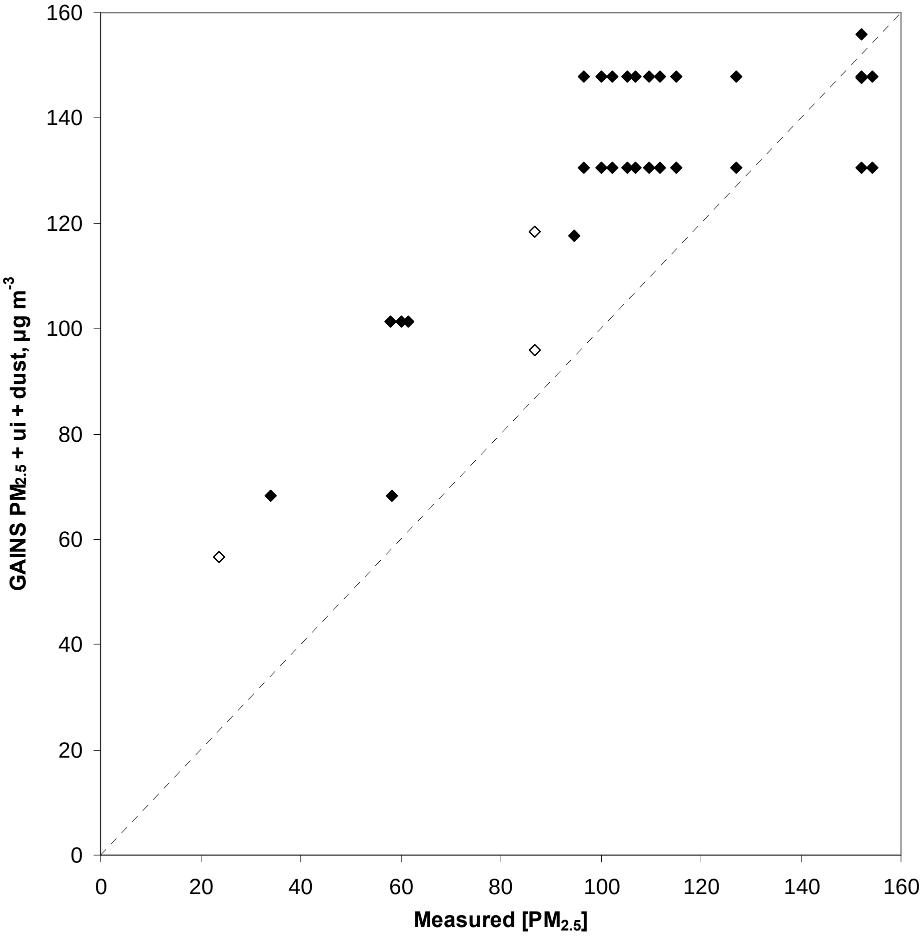


Figure 4.14: Comparison of GAINS estimates of $PM_{2.5}$ + urban increment + fine dust with available $PM_{2.5}$ measurements in Chinese cities. Open symbols represent rural sites for which no urban increment was applied to the GAINS estimate.

The small number of points in Figure 4.14, and their quantised appearance, indicate the relative scarcity of $PM_{2.5}$ measurements suitable for the validation. The large spread in measured values corresponding to one GAINS estimate is caused by the use of data for different measurement locations and/or different years for Beijing. The spread gives an indication of the variability in the measurements, all of which are compared with just one GAINS estimate for one grid cell.

Figure 4.14 suggests that the GAINS results have the correct relative magnitude but also show a clear tendency to overestimate the corresponding measured values. It is postulated that the reason behind this observation stems from the significant proportion of anthropogenic mineral dust accounted for in the GAINS emission estimates for China used in these calculations. This mineral dust is likely to exist predominantly in the PM_1 – $PM_{2.5}$ size range, and will therefore have a greater deposition velocity than smaller PM_1 particles and will have a shorter atmospheric lifetime. The GAINS transfer coefficients, however, are based on model experiments with black carbon (BC) which belongs to the PM_1 fraction. Using these transfer coefficients for the total $PM_{2.5}$ emissions – including a proportion of the larger fraction – will lead to an overestimate of the $PM_{2.5}$ concentration, as observed.

In order to take account of this effect, the calculated $PM_{2.5}$ transfer coefficients were adjusted by a factor based on the estimated relative abundance of the PM_1 and PM_1 – $PM_{2.5}$ size fractions in Chinese emissions. The comparison with measurements when the GAINS estimates are based on these modified transfer coefficients is shown in Figure 4.15. Although not perfect, the agreement with available measurements now exhibits considerably less bias.

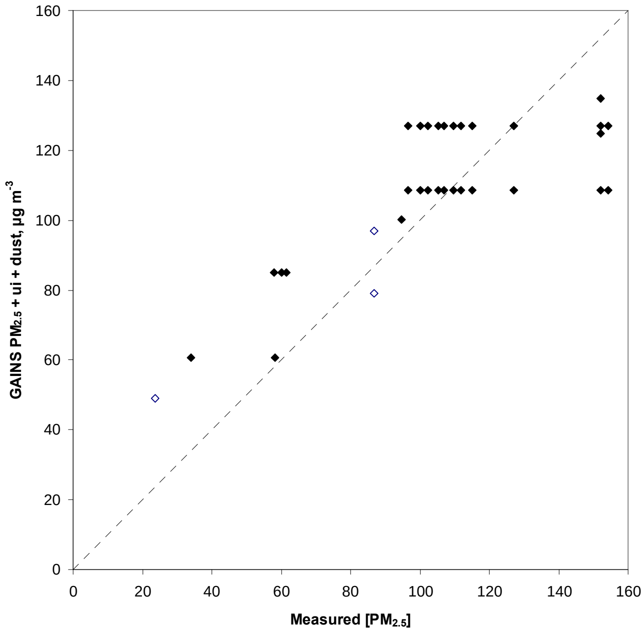


Figure 4.15: Comparison of GAINS estimates of $PM_{2.5}$ (using modified transfer coefficients) + urban increment + fine dust with available $PM_{2.5}$ measurements in Chinese cities. Open symbols represent rural sites for which no urban increment was applied to the GAINS estimate.

4.1.7 SUMMARY

A full validation of the GAINS $PM_{2.5}$ transfer coefficients for Asia through comparison with measurements is hampered by the relative scarcity of appropriate measurement data in these regions. The $PM_{2.5}$ measurements that are available in the literature are often restricted in geographical scope and are rarely made over sufficiently long time periods to provide a reliable estimate of the annual average $PM_{2.5}$ concentration.

Measurements of suspended particulate matter and/or PM_{10} have been made at a larger number of cities in India and China, and over sustained time periods. Using these as a basis for comparison with GAINS estimates of PM concentration, although associated with considerable uncertainties, suggest that the overall performance of the GAINS transfer coefficients is reasonably good. For both regions there is considerable scatter in the results – probably associated with uncertainties regarding the dust component. In China the errors appear to be distributed fairly randomly whereas the Indian comparison shows an underestimation of the measurements by the GAINS approach, particularly at higher concentrations.

The comparison of GAINS estimates with such $PM_{2.5}$ measurements as do exist also shows a reasonably good overall level of agreement. For this component, however, the GAINS results are clearly biased towards underestimates for Indian cities while in China the observed bias lies in the opposite direction.

In view of the uncertainties in both the modelled and measured values, the level of agreement found here is considered to be satisfactory.

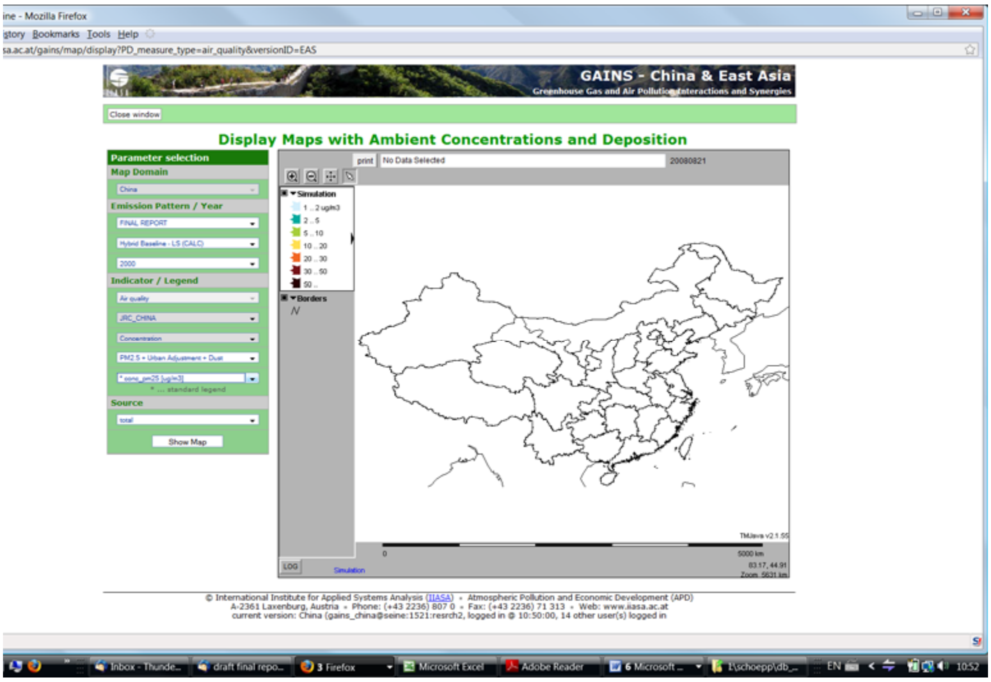
4.2 The Linkage between GAINS and TM5

To enable speedy estimates of air quality implications of user-defined emission control scenarios, the source-receptor relationships that have been developed with the TM5 model have been implemented in GAINS. Thereby, a user can obtain interactively with the GAINS interface over the Internet results from different emission control scenarios that are based on calculations with TM5.

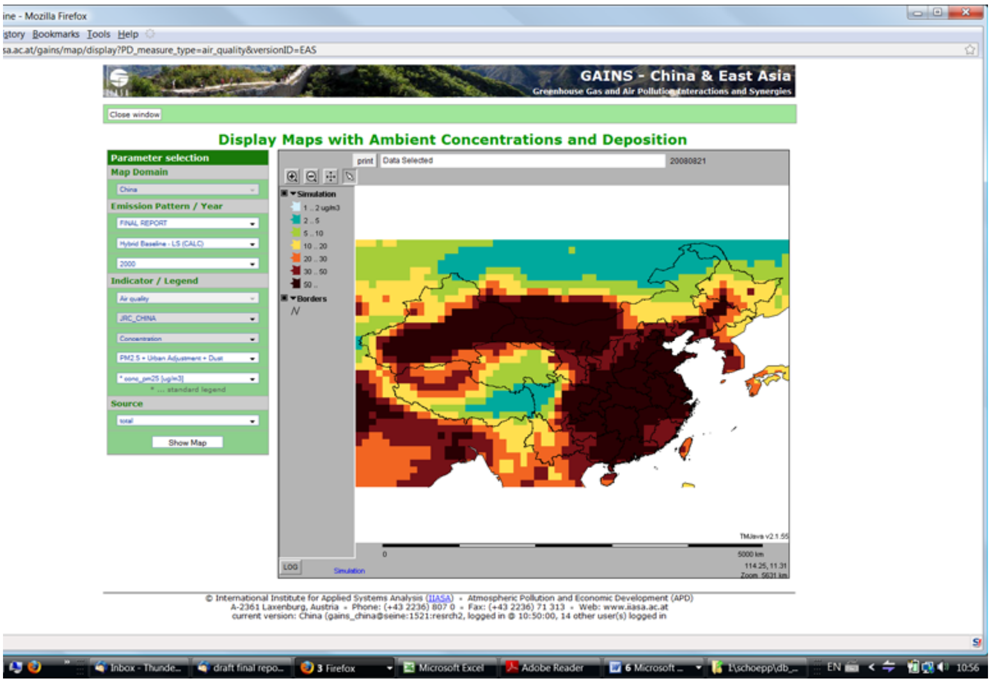
The GAINS model is freely accessible over the Internet (http://gains.iiasa.ac.at). After registration and login, a user can either define an own emission control scenario, or further analyze air quality implications of an already stored emission control scenario. The following screen shots provide an example session for China; the same analysis can be conducted for India.

To explore air quality impacts, the a user needs to select the "Impacts" tab on the menu.

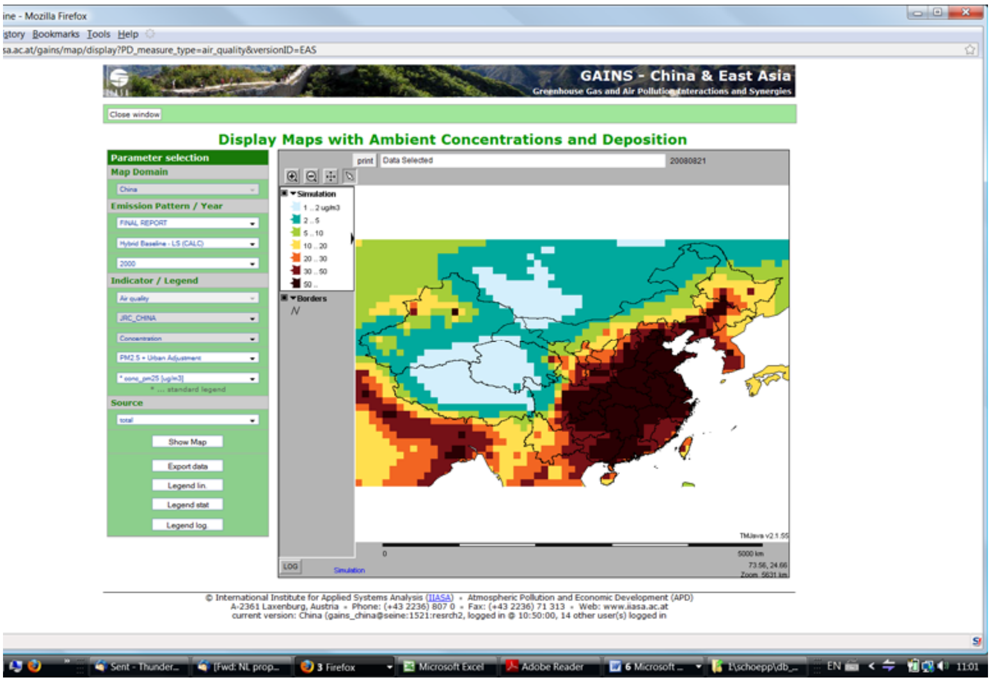
From there, a user can choose to obtain results in graphical (maps) or numerical form. In a next step, the user has to specify the emission control scenario and the year of interest. After that, the user needs to chose the desired air quality indicator (PM2.5 rural concentrations/PM2.5 with urban adjustments/PM2.5 with soil dust/PM2.5 from primary emissions of PM (excluding secondary aerosols)/ozone SOMO35 indicator, etc.), and choose a legend colour scheme.



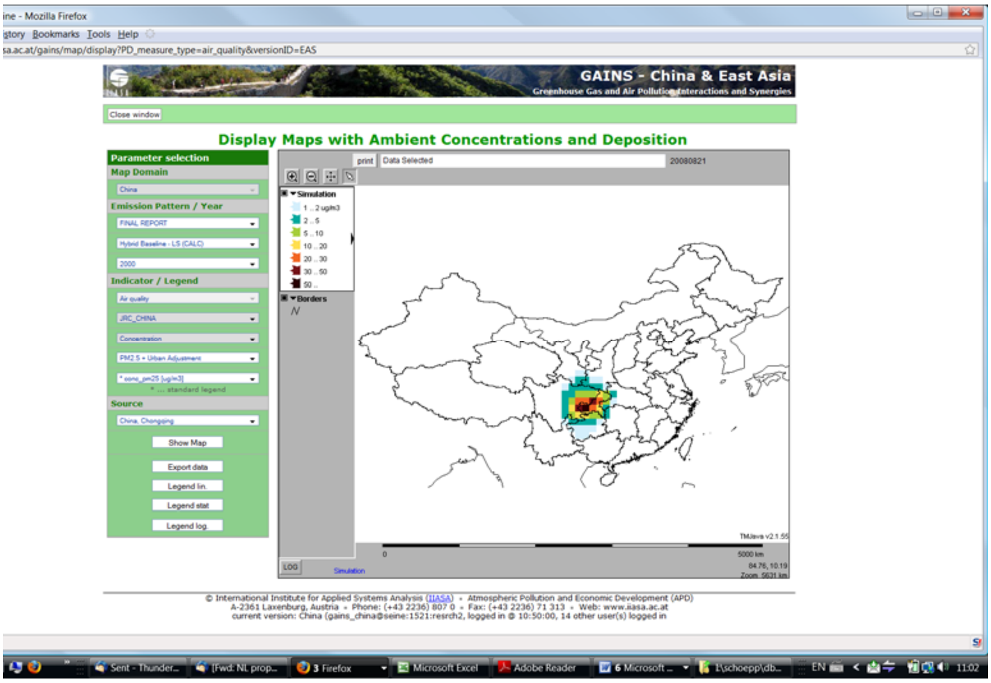
After all selections have been taken, the user will be provided with computed concentrations for the model domain.



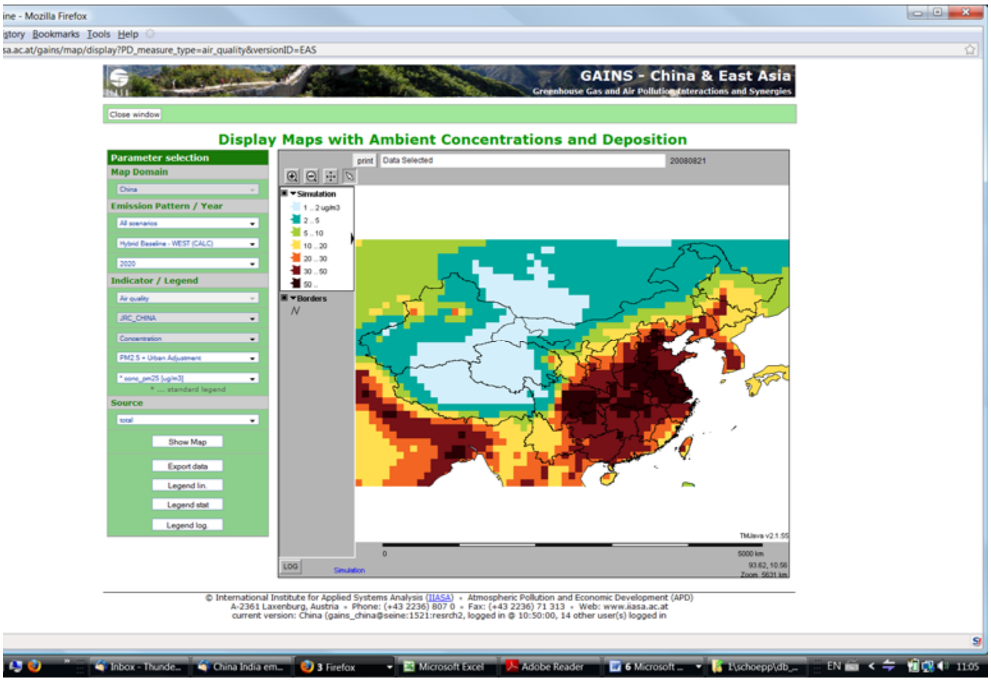
The GAINS interface enables displaying the contributions from each single source region and category; for instance, the tool can be used to display concentrations that result from anthropogenic emissions only:



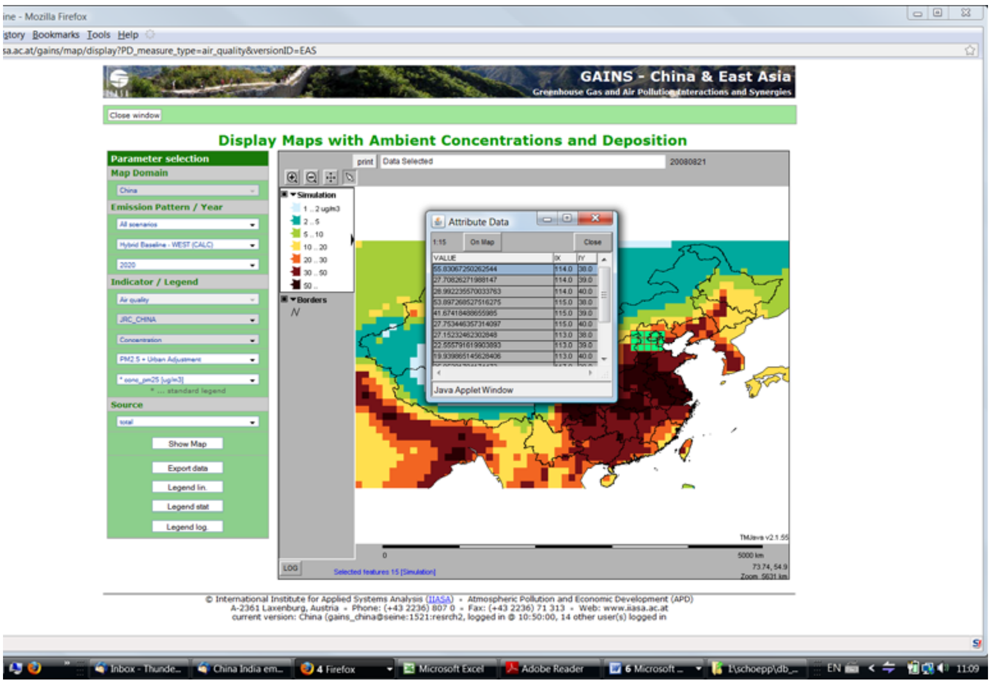
Or alternatively, the contributions from a single source region can be displayed (e.g., for Chongqing):



This analysis can then be repeated for different emission control scenarios and for different years. For instance, the following screen shot shows PM concentrations from anthropogenic sources in 2020 assuming stringent control of all emissions according to emission standards that prevail at present in Europe:



Results can be inspected in numerical form by marking the desired region for which numerical results will be displayed in a pop-up window (providing computed concentrations and x/y coordinates of the selected grid cells):



Visa versa, updated emissions resulting from GAINS for present day and two scenarios have been implemented in the context of global POLES scenarios as displayed in the figure below; given the calculated increase of PM10 concentrations by 2030 using a worldwide Business as Usual scenario, and the India/China specific BAU scenarios developed by TERI/ERI. This post-analysis is necessary to verify whether source-receptor relationships can be utilized beyond the tested range (-20 %). This analysis is currently ongoing.

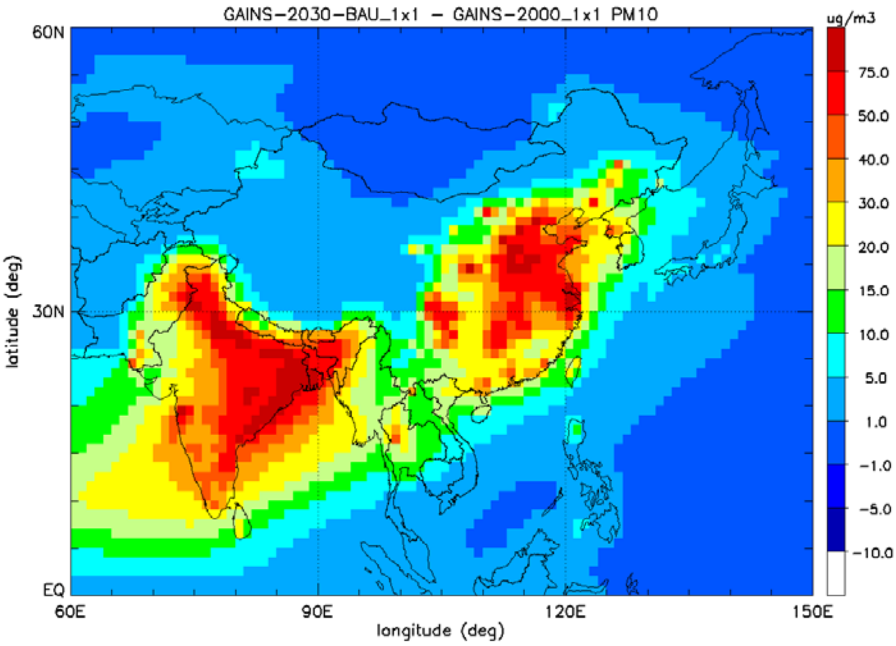


Figure 4.16: TM5 modelled increase of PM10 concentrations by 2030 using a worldwide Business as Usual scenario derived from the POLES model, and the India/China specific BAU scenarios developed by TERI/ERI during the GAINS-ASIA project. Further increases by up to 75 µg/m^3 are calculated for these scenarios.

5 Impact assessment

5.1 Health effects of fine particulate matter in outdoor air

5.1.1 APPROACH

The GAINS model estimates, for the population older than 30 years, long-term health impacts from fine particulate matter based on cohort studies in terms of years of life lost (YOLLs) and the loss in statistical life expectancy. The basic methodology follows the approach recommended by the Task Force on Health (TFH, 2003) as described in Mechler *et al.*, 2002.

The GAINS model quantifies for different emission scenarios premature mortality that can be attributed to long-term exposure to PM2.5, following the outcomes of the American Cancer Society cohort study (Pope *et al.*, 2002).

Cohort- and country-specific mortality data extracted from life table statistics are used to calculate for each cohort the baseline survival function over time. The survival function $l_c(t)$ indicates the percentage of a cohort c alive after time t elapsed since starting time w_0. $l_c(t)$ is an exponential function of the sum of the mortality rates $\mu_{a,b}$, which are derived from life tables with a as age and b as calendar time. As the relative risk function taken from Pope *et al.*, 2002 applies only to cohorts that are at least w_0=30 years old, younger cohorts were excluded from this analysis. Accordingly, for a cohort aged c, $l_c(t)$ is:

$$l_c(t) = \exp\left(-\sum_{z=c}^{t} \mu_{z,z-c+w_0}\right). \tag{8}$$

The survival function is modified by the exposure to PM pollution, which changes the mortality rate and consequently the remaining life expectancy (e_c). For a given exposure to PM2.5 (PM), life expectancy $\bar{l}_c$ is calculated as the integral over the remaining life time:

$$e_c = \int_c^{w_1} \bar{l}_c(t)\,dt = \int_c^{w_1} \exp\left(-RR_{PM} \sum_{z=c}^{t} \mu_{z,z-c+w_0}\right)dt \tag{9}$$

where w_1 is the maximum age considered and RR_{PM} the relative risk for a given concentration of PM2.5. With some simplifying assumptions and approximations (Vaupel and Yashin, 1985), the change in life expectancy per person (Δe_c) of a cohort c can be expressed as:

$$\Delta e_c = \beta PM \int_c^{w_1} l_c(t) \log l_c(t)dt \tag{10}$$

where – within the studied exposure range – RR_{PM} has been approximated as $RR_{PM}= \beta \cdot PM+1$ with β = 0.006 as given in Pope *et al.*, 2002. For all cohorts in a country l the change in life years ΔL_l is then calculated as the sum of the change in life years for the cohorts living in the grid cells j of the country l:

$$\Delta L_l = \sum_{c=w_0}^{w_1} \Delta L_{c,i} = \beta \sum_{j \in l} PM_j \frac{Pop_j}{Pop_l} \sum_{c=w_0}^{w_1} Pop_{c,l} \int_c^{w_1} l_c(t) \log l_c(t) dt \qquad (11)$$

where

$\Delta L_{c,l}$	*Change in life years lived for cohort* c *in country* l
$Pop_{c,l}$	Population in cohort *c* in country *l*
Pop_j	Total population in grid cell *j* (at least of age w_0=30)
Pop_l	Total population in country *l* (at least of age w_0=30).

5.1.2 IMPLEMENTATION FOR CHINA AND INDIA

For Asia (i.e., China, India, Pakistan), the GAINS analysis uses

- annual mean PM2.5 concentrations of primary particulate matter (black carbon, organic carbon, other organic matter, mineral dust, etc.) and secondary inorganic aerosols emitted from anthropogenic sources as calculated with the GAINS model (based on TM5 calculations), distinguishing in each grid cell urban background and rural concentrations. The health impact calculation does not quantify impacts from emissions from natural sources and of secondary organic aerosols.
- population maps with a 1*1 degree resolution distinguishing urban and rural population in each grid cell
- population projections by cohort up to 2030 from IIASA's World Population programme by country,
- epidemiological evidence on premature mortality as reported by Pope *et al.*, 2002 for the United States and the relative risk numbers given in this paper,
- life tables that quantify current mortality rates for different cohorts for China, India, Pakistan, as well as the life table of Japan, from the UN population database.

The current GAINS calculation assumes a linear exposure-response curves up to the concentrations calculated for future years (i.e., up to 200 µg/m^3) based on the findings of the PAPA study (HEI, 2004).

Obviously, such calculations include numerous uncertainties, which are impossible to be eliminated at the present time. To provide an indication of the resulting uncertainty range, GAINS estimates results for a set of alternative hypotheses, and then presents as the central estimate the ensemble mean of the different calculations.

In particular, GAINS considers the following uncertainties:

- The applicable rate of relative risk, especially for high concentrations for which no observational evidence is available from the existing literature. The current GAINS algorithm does not allow the use of non-linear concentration-response curves, through which declining effects of the relative risk at high concentrations could be represented. Instead, the analysis explores the use of two relative risk factors, i.e., one that has been derived by Pope *et al.*, 2002 for the entire time period (i.e., RR=1.06), and one that has been derived for the earlier study period (1990-2000), in which the mix of air pollutants was more dominated by sulphates and which could be considered as more representative for current Asian conditions (RR=1.04).

- The baseline mortality rates from which additional mortality is calculated. The reference study (Pope *et al.*, 2002) derived relative risk figures for the mortality rates of the United States, which represent mortality of a wealthy society with a well developed health service. Mortality rates observed in developing countries are substantially higher. Assuming that incremental mortality from air pollution is not influenced by other living conditions, application of the relative risk factors derived for US mortality rates would thus overestimate mortality that could be attributed to PM. However, there is evidence in the literature that air pollution also increases mortality in a population that is frail due to other conditions.

Thereby, the GAINS analysis explores the following four cases:

- A relative risk factor of **1.06** (for the entire period in Pope *et al.*, 2002), and **the country-specific mortality rates** derived from the national life table, applied to the number of people of population projection
- A relative risk factor of **1.06** (for the entire period in Pope *et al.*, 2002), and the Japanese mortality rates derived from the national life table, applied to the number of people of population projection
- A relative risk factor of **1.04** (for the entire period in Pope *et al.*, 2002), and **the country-specific mortality rates** derived from the national life table, applied to the number of people of population projection
- A relative risk factor of **1.04** (for the entire period in Pope *et al.*, 2002), and the Japanese mortality rates derived from the national life table, applied to the number of people of population projection.

As the central estimate, GAINS presents the mean of the ensemble results of the four cases presented above.

5.1.3 SUMMARY OF ASSUMPTIONS

Following the approach as outlined above, the GAINS health impact assessment employs the following assumptions:

- Health impacts are related to the human exposure to PM2.5 from anthropogenic sources of
    - o primary particulate matter (black carbon, organic carbon, other organic matter, mineral dust, etc.),
    - o Secondary inorganic aerosols formed from emissions of SO_2, NO_x, NH_3.
- No health impacts are quantified for exposure of PM2.5 from
    - o natural sources,
    - o secondary organic aerosols.
- In urban areas, health effects in the urban population are correlated with annual mean urban background concentrations.

- Health impacts of PM are calculated for exposed population older than 30 years. No effects are estimated for children.
- The calculation assumes that individuals will remain exposed to the exposure level calculated for 2020 for the rest of their life time
- Validity of a linear concentration-response curve up to 200 μg/m^3 (a sensitivity case with a cut-off at 100 μg/m^3 will be presented.
- Validity of relative risk factors as identified in Pope *et al.*, 2002, sensitivity analysis for RR=1.06 and RR=1.04
- Baseline mortality rates (a) that are actually observed in the country, and (b) of Japan, representing the mortality rates of a population with good health services (to exclude higher mortality that is attributable to a lower development status).

5.2 Health effects of ground-level ozone in outdoor air

Based on a comprehensive meta-analysis of time series studies conducted for the World Health Organization (Anderson *et al.*, 2004) and on advice received from the UNECE/WHO Task Force on Health (UNECE/WHO, 2004), the GAINS model quantifies premature mortality through an association with the so-called SOMO35 indicator for long-term ozone concentrations in ambient air. SOMO35 is calculated as the daily eight-hour maximum ozone concentrations in excess of a 35 ppb threshold, summed over the full year. In essence, the GAINS calculation estimates for the full year daily changes in mortality as a function of daily eight-hour maximum ozone concentrations, employing the concentration-response curves derived in the meta-analysis of Anderson *et al.*, 2004. The threshold was introduced (i) to acknowledge uncertainties about the validity of the linear concentration-response function for lower ozone concentrations, and (ii) in order not to overestimate the health effects. The annual cases of premature mortality attributable to ozone are then calculated as

$$Mort_l = \tfrac{2}{365} Deaths_l \cdot RR_{O3} \cdot O3_l \qquad (12)$$

where

$Mort_l$	*Cases of premature mortality per year in country* l
Deaths$_l$	Baseline mortality (number of deaths per year) in country *l*
RR_{O3}	Relative risk for one percent increase in daily mortality per μg/m^3 eight-hour maximum ozone concentration per day.

In addition to the mortality effects, there is clear evidence about acute morbidity impacts of ozone (e.g., various types of respiratory diseases). However, the GAINS model quantifies only mortality impacts of ozone, as they emerge as the dominant factor in any economic benefit assessment. Morbidity impacts will be quantified ex-post in the benefit assessment.

5.3 Health impacts from indoor pollution

GAINS estimates for Asian countries health impacts from indoor air pollution following the methodology employed for the Global Burden of Disease (GBD) project of the World Health

Organization (Smith *et al.*, 2004b).

The environmental burden of disease quantifies the amount of disease caused by environmental risks. Disease burden can be expressed in deaths, incidence or in Disability-Adjusted Life Years (DALY). The latter measure combines the burden due to death and disability in a single index. Using such an index permits the comparison of the burden due to various environmental risk factors with other risk factors or diseases. GAINS model holds data on current and future use of solid fuels in the domestic sector for each source region, which can be readily used to estimate the number of households using solid fuels and the number of affected people in the different age cohorts.

The methodology developed by the World Health Organization (WHO) for the Global Burden of Disease project (Smith *et al.*, 2004b) is implemented in the GAINS model. The risk factors identified in Smith *et al.*, 2004a are applied to the exposed population, and the attributable burden due to solid fuel use is estimated as a product of attributable fraction for solid fuel use and current disease level. The attributable fraction, AF_{sfu}, can be estimated as Desai *et al.*, 2004

$$AF_{sfu} = \left[\frac{p_e (r_r - 1)}{p_e (r_r - 1) + 1} \right] \tag{13}$$

where p_e represents the population exposed to the solid fuels and r_r the relative risk due to solid fuel use.

Similarly, attributable burden due to the solid fuel, AB_{sfu}, use can be estimated as

$$AB_{sfu} = AF_{sfu}\, CDL = \left[\frac{p_e (r_r - 1)}{p_e (r_r - 1) + 1} \right] CDL \tag{14}$$

where CDL represents the current disease level.

For this calculation GAINS requires the following information/data: a) number of households in GAINS regions, b) percentage of households using coal, c) percentage of households using solid fuels except coal (i.e., fuelwood, dung, agri-residues, etc.), d) total number of DALYs in each GAINS region (e.g., Indian State, Chinese Province) for each health outcome and group (sex, age in years), and relative risk for each health outcome and group (sex, age in years).

The GAINS model provides macro-economic data on population in the GAINS regions and fuel mix in the domestic sector, which allow derivation of many of the required data. Further details on the methodology and data sources are provided in Purohit, 2008.

5.4 Vegetation impacts from ground-level ozone

5.4.1 BACKGROUND

Elevated levels of ozone have been shown to cause widespread damage to terrestrial vegetation. Field experiments have demonstrated reductions in the yield of sensitive crop species in Europe and N. America (Krupa *et al.*, 1998) and also, more recently, in Asia and other parts of the world (Emberson *et al.*,). Increasingly, attention is being paid to the likely extent of the problem in Asia where rapid economic development is expected to lead to greater emissions of ozone precursors in areas experiencing an increasing demand for food.

A number of studies have addressed the issue of ozone-induced crop losses in Asia. A modelling exercise by Aunan *et al.*, 2000 assessed reductions in the yields of rice, wheat, soybean and maize in China in 1990 and potential losses for 2020. They found that crop production may be reduced substantially in the future, under the emission scenario considered, and was possibly already affected for some crops. A similar study for East Asia for the same years (Wang and Mauzerall, 2004) reached a similar conclusion but estimated generally higher relative yield losses (e.g., 6-13% for winter wheat, 15-23% for soybean in China in 1990). More recently, Van Dingenen *et al.*, evaluated the global impact of surface ozone on agricultural crops for the years 2000 and 2030. Their results suggested regionally-aggregated relative yield losses in the range 3 – 19 percent in China and 2 – 28 percent for India, depending on crop type and exposure indicator used. The general conclusion of these model studies is supported by a survey of available measurements of ground-level ozone in China (Wang *et al.*, 2007), which, despite the paucity of measurement data, showed that present ozone concentrations exceed critical levels for the protection of crops.

5.4.2 EXPOSURE INDICES

A number of different empirical exposure-response relationships between ozone levels and changes in crop yields have been employed in assessments of crop losses due to ozone. Both concentration-based and flux-based approaches have been described.

Concentration-based approaches include indices derived from seasonal mean daytime concentrations and those based on accumulated exposure, often the exposure above a threshold concentration. The first type were originally developed from the NCLAN experimental programme in the USA (Heck *et al.*, 1988) and use the seasonal mean daytime concentration typically averaged over periods of 7 (termed M7), 8 or 12 hours (M12).

A commonly-used accumulated exposure index is the AOT40, the seasonal accumulated exposure above 40 ppb during daylight hours, originally developed to assess data from open-top chambers in Europe (Fuhrer *et al.*, 1997). Other examples include the SUM06 (with a 60 ppb threshold) and W126, which uses a weighting function rather than a threshold value to give greater weight to higher concentrations. The use of cumulative ozone exposure indices has generally been favoured over those based on mean concentrations.

The flux-based method developed in Europe (Pleijel *et al.*, 2004; Karlsson *et al.*, 2004; Pleijel *et al.*, 2007) uses the accumulated stomatal flux of ozone above a critical flux threshold to allow for the fact that ozone effects are more closely related to ozone flux into the leaf than to external concentrations. While the theoretical advantage of the flux concept is widely accepted, since it more closely reflects important physiological processes, its critical parameters have been evaluated for a relatively small number of crop types.

5.4.3 GAINS APPROACH

The GAINS model assesses the impact of ground-level ozone in Asia on four types of crop: rice, wheat, maize and soybean. The relative economic importance of these crops is indicated in Table 5.1, which shows the total value of their production in China and India in 2000, and lists their ranking, by value, within the food and agricultural commodities of each country for that year according to FAO statistics (http://www.fao.org/es/top/country.html).

Table 5.1: Value, in $ million, and ranking of crop production in China and India in 2000.

Crop	China		India	
	Production value	Rank	Production value	Rank
Rice	40026	1	27137	1
Wheat	15541	4	11912	3
Maize	12317	5		
Soybean	3358	15		

Such an assessment requires the following information:

- an exposure index relating crop yield reductions to ozone exposure;
- functional relationships between ozone exposure and precursor emissions; and
- data on crop production in Asia.

The data sources employed in GAINS are described briefly in the following sections.

Yield response functions

For pragmatic reasons of data availability, GAINS uses the AOT40 exposure index as a means to assess potential reductions in crop yields due to surface ozone. The AOT40 indicator is calculated as the sum of hourly ozone concentrations above a threshold of 40 ppb during daylight hours when clear sky radiation ≥ 50 Wm^{-2}, accumulated for three months over the most sensitive vegetation period:

$$AOT40 = \sum_{i=1}^{n} \{[O_3] - 40\}_i \qquad \text{for } [O_3] > 40 \text{ ppb} \tag{15}$$

where

$[O_3]$	hourly ozone concentration, ppb
n	number of hours (i) that the threshold of 40 ppb is exceeded

A recent synthesis of AOT40-based response functions (Mills *et al.*, 2007) reviewed a wide range of crop response data to derive AOT40 yield response functions for 19 crops, including the four considered in GAINS. These functions are linear:

$$rel.yield = m \cdot AOT40 + c \tag{16}$$

where

rel. yield	relative crop yield
AOT40	AOT40, ppm.h

The intercept, *c*, of the functions is not, in general, equal to unity (0.94, 0.99, 1.02 and 1.02 for rice, wheat, maize and soybean, respectively). To avoid problems at relatively low values of AOT40, the offset of the intercept from one is ignored in GAINS, which uses the slopes of the reported yield-response functions (Table 5.2) in estimating relative crop yield losses. This approach appears to be consistent with that used in calculating the critical levels corresponding to a 5% yield reduction reported in Mills *et al.*, 2007.

Table 5.2: Slopes of AOT40-based crop yield response functions (AOT40 in ppm.h)

Crop	*Slope of response function*
Rice	-0.0039
Wheat	-0.0161
Maize	-0.0036
Soybean	-0.0116

Atmospheric chemistry and transport

The GAINS assessment needs to link changes in the ozone precursor emissions at the various sources to responses in the relevant exposure indicator at a receptor grid cell *j.* The joint analysis with economic and ecological aspects in the GAINS model, and especially the optimization task, requires computationally efficient source-receptor relationships. For this reason, GAINS assumes that changes in the AOT40 exposure indicator can be described sufficiently accurately by a linear formulation:

$$AOT40_{c,j} = AOT40_{c,j,0} - \sum_i N_{c,i,j}(n_{i,0} - n_i) - \sum_i V_{c,i,j}(v_{i,0} - v_i) \qquad (17)$$

where

$AOT40_{c,j}$	vegetation-relevant seasonal ozone exposure indicator measured as the crop-specific AOT40 for crop *c* in receptor grid cell *j*
$AOT40_{c,j,0}$	AOT40 for crop *c* in receptor grid cell *j* due to reference emissions n_0, v_0
n_i, v_i	emissions of NO_x and VOC in source region *i*
$N_{c,l,j}$, $V_{c,i,j}$	coefficients describing the changes in the AOT40 indicator for crop *c* in receptor grid cell *j* due to emissions of NO_x and VOC in source region *i.*

The necessary sets of transfer coefficients, $N_{c,l,j}$, $V_{c,i,j}$, have been derived from the results of model experiments performed with the TM5 global chemical transport model (Krol *et al.*, 2005; Ellingsen *et al.*, 2008), based on a reference case using NO_x and VOC emission estimates for the year 2000 and meteorological data for 2001. Modelled changes in ozone concentration at 1° x 1° receptor grid cells resulting from 20% reductions in NOx and VOC emissions from each source region applied separately were used to calculate changes in the crop-specific AOT40 indicators for appropriate growing seasons. The source regions considered were typically states in India and provinces in China. The resulting sets of source-region-to-grid-cell transfer coefficients are used to estimate the AOT40 exposure indices for different emission scenarios, assuming that non-linear effects may be neglected.

5.4.4 CROP PRODUCTION

The estimation of crop losses due to ozone requires actual crop production data, in addition to the calculated relative yield losses. For the GAINS model such information was provided by IIASA's LUC programme. Crop production estimates for the year 2000 for each relevant 1° x 1° grid cell in China were obtained by aggregating published statistics available at the county level. The corresponding data for India were calculated from crop production statistics for individual states, the most detailed level reported. Crop production was apportioned to individual grid cells on the basis of the crop-specific Global Agro-Ecological Zones (GAEZ) modelled suitability index (Fischer *et al.*, 2002). The GAEZ model was used to identify grid cells in which edaphic and climatic conditions are favourable for the cultivation of each crop. Subsequently, the reported production statistics at state level were downscaled to each 1° x 1° grid cell in proportion to the attainable yields estimated by GAEZ.

Figure 5.1 shows the spatial distribution of rice, wheat, maize and soybean production in 2000 in China. The corresponding maps for India are shown in Figure 5.2.

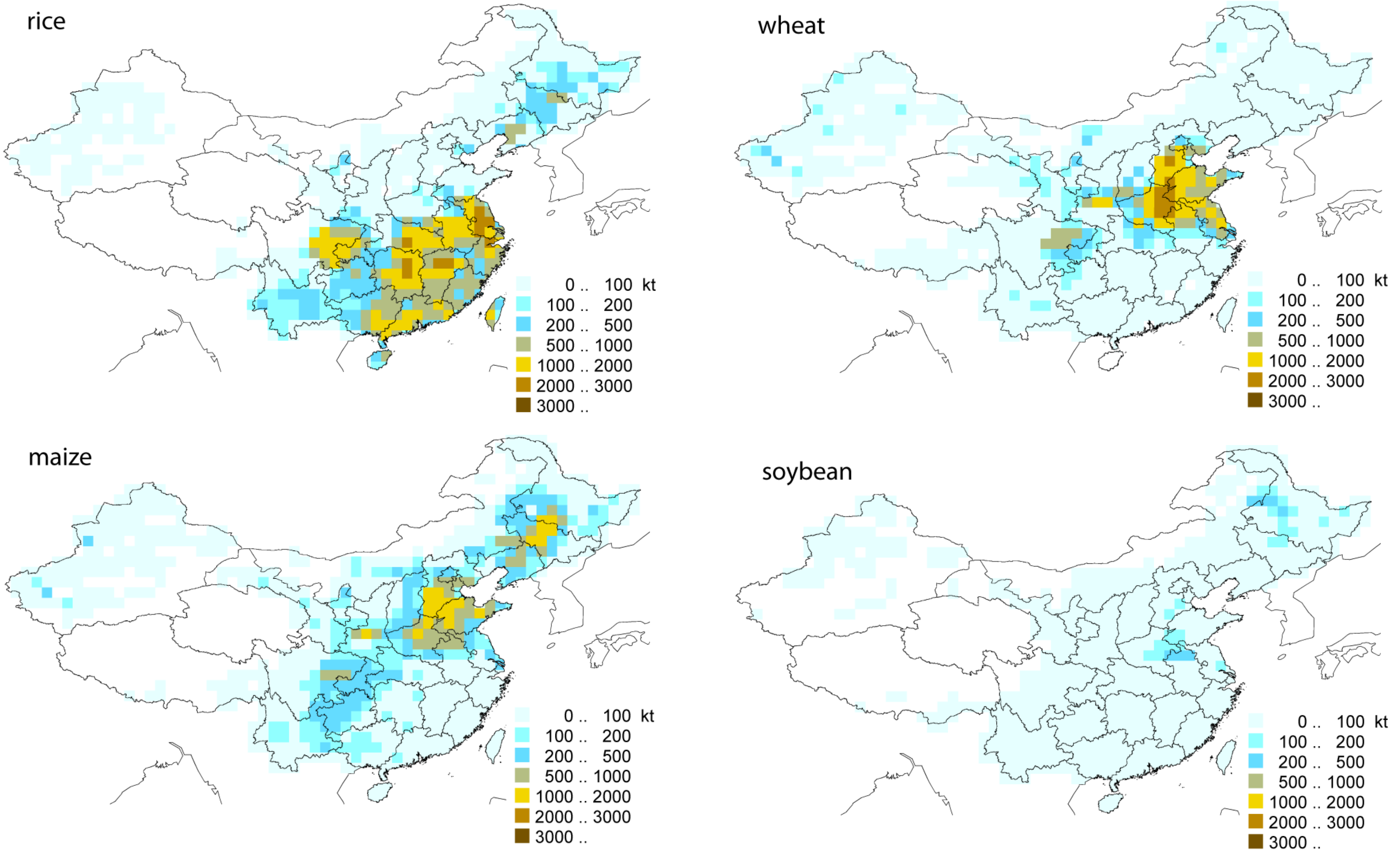


Figure 5.1 Annual production of crops in China in 2000 (kt per 1° x 1° grid cell)

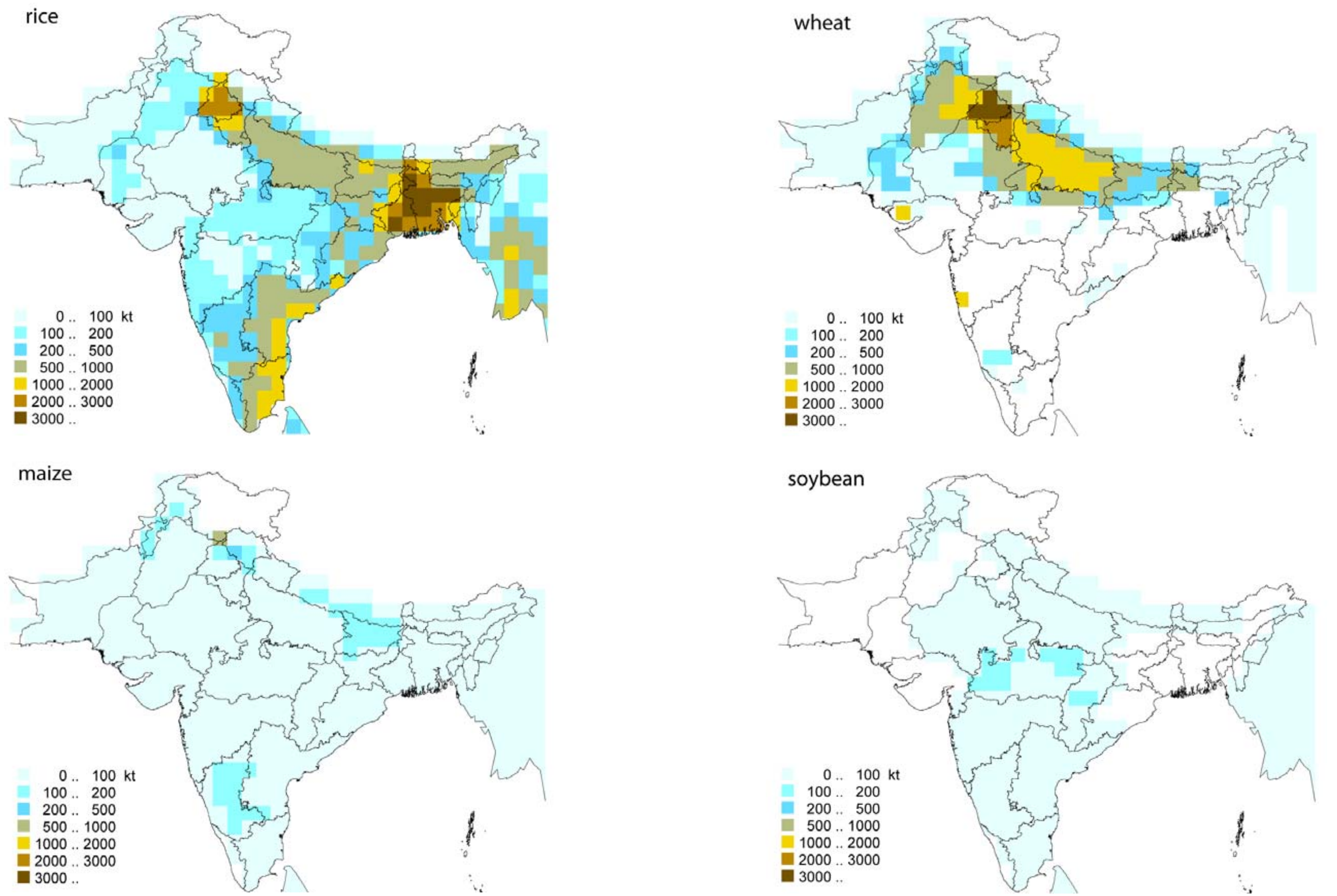


Figure 5.2 Annual production of crops in India in 2000 (kt per 1° x 1° grid cell)

5.4.5 CAVEATS

While the methodology described above is believed to be appropriate for an integrated assessment tool such as GAINS, there are a number of factors to remember when considering the results:

- A validation scenario for testing the AOT40 calculation is not yet available. There is an urgent need to assess the results of calculations using the GAINS linear transfer coefficients against TM5 model results for emissions scenarios covering the expected range in which GAINS is likely to be applied.
- The scarcity of surface ozone measurement data in Asia for comparison with the GAINS estimates is another barrier to adequate validation of the GAINS approach.
- While it is argued that, for practical reasons, the AOT40 exposure index is the most appropriate indicator to use within GAINS, its limitations with respect to reflecting actual plant physiological processes should not be forgotten.
- As in other studies, GAINS applies yield response functions derived for European and American conditions to Asian crops. These relationships may, however, underestimate the ozone sensitivity of equivalent crops and varieties grown under Asian conditions (Emberson *et al.*,).

6 The GAINS cost-effectiveness optimization

The optimization model of GAINS uses two types of decision variables: (i) activity variables $x_{i,k,m}$ for all countries i, activities k, and control technologies m, and (ii) the substitution variables $y_{i,k,k'}$ that represent fuel substitutions and efficiency improvements (replacing activity k by activity k'). The objective function that is minimized is the sum

$$C = \sum_{i,k} \left(\sum_m c^x_{i,k,m} \cdot x_{i,k,m} + \sum_{k'} c^y_{i,k,k'} y_{i,k,k'} \right) \tag{18}$$

where the first term represents the total end of pipe technologies cost, and the second term represents the total substitution/energy efficiency cost term. In order to avoid double counting the substitution cost coefficients $c^y_{ikk'}$ in the second term are calculated for uncontrolled activities, the difference in cost for control equipment for a fuel substitution is accounted for in the first term.

It is convenient to consider the activity data $x_{i,k}$, which are obtained from the variables $x_{i,k,m}$ by performing the appropriate sum over control technologies m. Activity data as well as the substitution variables may be constrained:

$$x^{\min}_{i,k,m} \le x_{i,k,m} \le x^{\max}_{i,k,m}, \quad x^{\min}_{i,k} \le x_{i,k} \le x^{\max}_{i,k}, \quad y^{\min}_{i,k,k'} \le y_{i,k,k'} \le y^{\max}_{i,k,k'} \tag{19}$$

due to limitations in applicability or availability of technologies or fuel types.

The applicability of add-on technologies may be constrained by a maximum value:

$$x_{i,k,m} \le appl^{\max}_{i,k,m} x_{i,k}, \quad appl^{CLE}_{i,k,m} \le appl^{\max}_{i,k,m} \tag{20}$$

where the maximum application rate is at least as high as the application rate in the current legislation scenario. For ammonia (NH_3), technologies in the agricultural (livestock) sector are subdivided into technologies applying to different stages of manure treatment. For these technologies, application constraints are applied at a more aggregated level.

Emissions of pollutant p are calculated from the technology-specific activity data $x_{i,k,m}$ and their associated emission factors $ef_{i,k,m,p}$:

$$E_{i,p} = \sum_k \sum_m ef_{i,k,m,p} \cdot x_{i,k,m} \tag{21}$$

Since for no individual activity k emissions should increase above the current legislation level, it is further imposed that

$$\sum_m ef_{i,k,m,p} \cdot x_{i,k,m} \le IEF^{CLE}_{i,k,p} \cdot x_{i,k} \tag{22}$$

where $ef_{i,k,m,p}$ is the emission factor for pollutant p stemming from activity k being controlled by technology m, and $IEF_{i,k,p}^{CLE}$ is the implied, i.e., average emission factor for that pollutant from activity k in country i in the current legislation scenario.

Activity variables $x_{i,k,m}$ are linked to the substitution variables $y_{i,k,k'}$ via the balance equations

$$x_{i,k} + \sum_{k'} y_{i,k,k'} - \sum_{k'} \eta_{i,k,'k} \cdot y_{i,k,'k} = x_{i,k}^{CLE} \quad (23)$$

where $x^{CLE}_{i,k}$ is the activity k in country i in the current legislation scenario and $\eta_{i,k,k'}$ is the substitution coefficient that describes the relative efficiency change in the transition from activity k' to activity k. For example, in the energy sector this last equation is balancing the energy supply before and after a fuel substitution. There are also a number of constraints which ensure consistency across various levels of aggregations of sub-sectors and sub-activities.

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