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Report on spatial emissions downscaling and concentrations for health impacts assessment

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1. Introduction

The link between climate change and air pollution is becoming more evident and can no longer be disregarded in policy making and implementation of emission control strategies. Even if the impacts and scales (time and spatial) of climate change and air pollution are quite diverse recent literature increasingly points to a number of interactions on different fronts that need to be taken into consideration. Air pollutants and greenhouse gases (GHGs) interact in several ways. This link can both lead to co-benefits or trade-offs when attempting the reduction of climate change impacts and the improvement air quality. Many air pollutants also have prominent role as radiative forcers and, therefore, regulating their emissions will, as well, have an effect on climate (and vice-versa). Ozone, and its precursors, and particulate matter (especially black carbon and sulphate) are both important pollutants and radiative forcers that can, directly or indirectly, contribute to climate change. Furthermore, a variation of atmospheric conditions resulting from climate change will affect the atmospheric concentrations of the compounds altering, therefore, the air quality. One other common aspect to both problems are emission sources. Many air pollutants and GHGs are emitted from the same sector, e.g. NOx and PM (pollutants) and CO_2 (GHG) both emitted from fossil fuel combustion. Emission reduction strategies devised by source can be a resourceful mode to achieve targets on different ends.

The full understanding of all the links and interactions between air pollution and climate change is not an easy undertaking. Several aspects have to be considered when attempting to take simultaneous action on both problems. On the one hand, the change in atmospheric composition and consequential impacts on humans and ecosystems occur in very different scales (e.g., the lifetime of most pollutants is quite short in comparison to the long lifetime of, for example, N_2O). On the other hand, some pollutants have a positive contribution to the radiative budget (e.g., black carbon, O_3) while others are cooling the atmosphere (e.g., sulphates and nitrates). Therefore, aiming at reduction of one problem does not necessarily lead to a decrease of the other and some trade-offs need to be weighted. For instance, the implementation of measures such as wood burning as biofuel to reduce use of fossil fuel and consequent climate impact may in fact deteriorate air quality by increased emissions of PM. Another example is the reduction of NH_3 emissions in agricultural sector that might lead to enhancement (or reduction) of N_2O and/or CH_4 depending on how it is implemented.

National air quality and climate policies do not usually deal with these issues together and are commonly disregarding possible feedbacks on one another. Still, it is undeniable that both problems need to be undertaken with a common action plan and there is great potential for more effective approaches that lead to a win-win situations for both climate and air quality. Additionally, the existence of cross-policy with co-benefits may incentivize their implementation if these are more effective measures with increased cost-benefits.

This topic has been addressed in different UNEP-WMO reports (UNEP/WMO, 2011 and UNEP, 2011) where climate-friendly air quality measures were proposed evaluating the benefits resulting from a hypothetical 100% implementation. Furthermore, also 'Clean Air For Europe' programme (CAFE) analysed potential links between air pollution and climate change generating

the adoption of the Thematic Strategy on Air Pollution. However, much can still be done as some main programs, such as Convention on Long-range Transboundary Air Pollution (CLRTAP) or United Nations Framework Convention on Climate Change (UNFCCC) do not yet address these issues on common grounds. Thus, in this context, there is a growing need for integrated analysis of the interaction between climate and air pollution goals. Optimization schemes supporting policy development and flexible tools that provide impact evaluation are becoming more common and advanced. Integrated assessment models are an example of such allowing for representation of climate change phenomena including a general change of society at economic and technological levels, accounting also for policy changes and current implementation. On the other hand source-receptor models focus mostly on determining the contribution of (change in) emissions from a certain source region to the pollution level of a receptor region. This source-receptor links are based not only on atmospheric chemistry but also downwind impacts. These models are useful to understand the contribution of specific sources (or even specific sectors) to the air quality on distant locations. In a time that air quality standards are becoming increasingly more thigh it is important for the nations to understand how much of the pollutants is in fact emitted from national sources or imported from other countries (not necessarily their neighbouring states). The TM5-FASST tool is one of such models that reproduces the source-receptor relation, determines the impact from air pollution on human health and ecosystems, and allows for the assessment of co-benefits of air quality and climate policies.

Global leaders gathered in 2009 in Copenhagen and came to an agreement that it would be essential to limit the global temperature increase to 2°C relative to pre-industrial times. According to the UNFCCC, this will "avoid dangerous anthropogenic interference with the climate system" (article 2) and, therefore, this is currently the target used as reference in national and international climate mitigation policy. In practice this means that the long-term concentration of GHGs cannot exceed the 450ppm of CO_2-equivalent (CO_2eq) which is a merely raise of 5% if one considers the estimated 430ppm of year 2000. The LIMITS project (Low climate IMpact scenarios and the Implications of required Tight emission control Strategies - http://www.feem-project.net/limits/index.html) was designed with the main goal of assessing strategies for reduction of GHG emissions so that the 2°C target can be achieved, exploring its implications on different levels and associated uncertainties. The work develop in this project focus on the evaluation of the implementation of strategies analysing several aspects of the scenarios, namely: the feasibility of low carbon scenarios with available technologies and foreseen difficulties; the required investment and financial mechanisms for such scenarios, and consequent changes in the energy infrastructure and land use; the co-benefits regarding energy security, air pollution and economic development. This project analyses scenarios both on a global level and for regional cases of key global economies, e.g. Brasil, USA, China, India. Several integrated assessment models (IAMs) run climate (and air pollution) mitigation and adaptation scenarios providing results for the LIMITS tasks (namely, air pollutants emissions). The TM5-FASST source-receptor model is part of the LIMITS project, providing a link between the air pollutant emissions resulting of the different scenarios and the impact calculation. With the results of the models we will investigate if stringent climate mitigation policies can be used together with local policy priorities, such as those for air pollution control. Furthermore, it will be important to determine what the regional/local benefits or trade-offs are from the climate mitigation actions towards the 2°C goal. Will reductions on urban air pollution take place and (or),

consequently, an improvement on human health? Are there any expected short-term trade-offs for the climate given the removal of short-lived cooling agents (e.g., sulphur and OC)?

This report addresses Deliverable D4.2 in the Work Package 'Multiple benefits of climate mitigation and implications for development'. Its content does not exclusively describe the spatial downscaling of model's emissions and sub-grid parameterization implemented to better represent the concentration increment of urban areas in contrast with rural ones. The present document also includes a description of the recent developments done in the TM5-FASST model in the framework of LIMITS. In the first section the model is described focusing on spatial scaling issues, the sub-grid parameterization and impact calculation, i.e., health impacts, assessment of crop yield and contribution of short-lived species to radiative forcing. Section 2 addresses the work done to within the LIMITS project context and in the last section the potential of TM5-FASST is exemplified by showing initial results of the LIMITS scenarios evaluation.

1.1 General methodology of TM5-FASST

JRC has developed during the past 5 years the global air quality source-receptor model (AQ-SRM) TM5-FASST (Van Dingenen and Dentener, 2013). In general, AQ-SRMs link emissions of pollutants in a given source region to impacts at the downwind receptor region, using knowledge of meteorology and atmospheric chemistry. The source region is any point or area from which emissions are considered; the receptor is any point or area at which the pollutant concentration and impact is to be evaluated. Pollutants can be primary (or passive), those that do not undergo chemical transformation during their atmospheric lifetime and are only affected by dry and wet removal from the atmosphere (e.g. elemental carbon, mineral dust). Alternatively, they can be secondary, in which case the emitted compound is transformed in one or more secondary components, e.g. NO_2 forms nitrate aerosol but also leads to the formation of O_3; emitted SO_2 is transformed into sulphate aerosols as secondary product. Another type of secondary effect is when emitted compounds indirectly affect the chemical formation of other secondary species, e.g. NO_2 has a (small) influence on the formation rate of SO_4 from SO_2. In summary, a specific secondary 'end product' can be formed from 1 or more emitted precursors, and an emitted precursor will lead to 1 or more end products (Table 1). An AQ-SRM will then include a functional relation between each precursor and each end product for each source region and each receptor region.

TM5-FASST is a reduced-form AQ-SRM: the relation between the emissions of compound *i* from source *x* and resulting pollutant *j* concentration (where *j=i* in case of a primary component) at receptor *y* is expressed by a simple functional relation which mimics the underlying meteorological and chemical processes. In the current version of TM5-FASST, the function is a simple linear relation: $C_{i\rightarrow j,y,x} = C_o + A_{i\rightarrow j,y,x} \cdot E_{i,x}$, where $C_{i\rightarrow j,y,x}$ is the concentration of species *j* at receptor *y* formed from precursor *i* emitted at source *x*, $E_{i,x}$ is the emission rate (kg/yr) of precursor *i* at source *x*, $A_{i\rightarrow j,y,x}$ is the so-called source-receptor coefficient (SRC) between *x* and *y* for (*i*→*j*) and C_0 is a constant.

The source-receptor coefficients are stored as matrices with dimension [x,y]. There is a single matrix for each precursor and for each resulting component from that precursor. The SRCs have been derived from a set of runs with the full chemical transport model TM5-CTM (Tracer Model, version 5) by applying emission perturbations for each of a defined set of source regions and precursor components. TM5-CTM is a state-of-the-art global atmospheric chemical transport model for gaseous pollutants and aerosols. It explicitly solves the mass balance equations of the species using detailed meteorological fields and sophisticated physical and chemical process schemes. The spatial resolution of the model is 6°x4° but nested zoom regions can be considered at the finer grid size of 3°x2° or 1°x1°. Further details on the definitions and assumptions of the model can be found in Krol et al. (2005). TM5-CTM has participated in numerous multi-model exercises and intercomparisons, such as UNECE HTAP, AEROCOM, ACCENT, and recently in the projects GEMS and MACC (Krol et al., 2005; Dentener et al., 2006; Stevenson et al., 2006; Eyring et al., 2007; Anenberg et al., 2009; Fiore et al., 2009; Jonson et al., 2010; Huijen et al., 2010). Furthermore, the model has been validated against surface, airborne and satellite observations in several exercises (e.g., various compounds in Huijen et al., 2010, O_3 crop metrics: Van Dingenen et al., 2009 and PM2.5: Rao et al., 2011).

More in particular, the applied procedure to calculate the SRCs was the following:

- 56 source regions were defined (see Figure 1) covering the continents;
- A base run with a reference emission dataset (AR5 RCP year 2000)[1] was performed including emissions from all major air pollutant precursors, like SO_2, NOx, BC, OC, NMVOC, and NH_3, producing the resulting base concentrations at a global 1°x1° resolution;
- A series of perturbation runs were performed, where sequentially in each of the defined 56 source regions, the emissions of each of the pollutants was reduced by 20% relative to the base run, over the entire source region, and the resulting change in concentration of all affected pollutant species was calculated. Hence, in principle, the number of perturbation runs is (56 x *n)*, with *n* the number of emitted compounds. In practice, in order to reduce the number of runs, some compounds were grouped into one perturbation simulation.

For each receptor point, the resulting delta concentration between base and perturbation run, leads to the calculation of a unique SRC:

$$A_{i\to j,y,x} = \Delta C_j(y) \big/ \Delta E_i(x), \text{ with } \Delta E_i(x) = 0.2 \cdot E_{i,base}(x).$$

Having established and stored all relevant source-receptor matrices, those are subsequently used to calculate the resulting concentration change from any emission by scaling them with actual emission changes. Hence, the total concentration of component *j* in receptor region *y*, resulting from emissions of all its precursors *i* at all source regions *x* is obtained from:

$$C_{i\to j}(y) = C_{j,base}(y) + \sum_x \sum_{i\to j} A_{i\to j,y,x} \cdot \left[E_i(x) - E_{i,base}(x)\right]$$

[1] Representative Concentration Pathways (tntcat.iiasa.ac.at:8787/RcpDb) from the Fifth Assessment Report of IPCC (https://www.ipcc.unibe.ch/AR5/)

In the case of j=O_3, the i precursors would comprise [NOx, NMVOC, CO, CH_4]. An overview of all considered precursor-pollutant combinations are given in Table 1. This set of linear equations for all components and all source and receptor regions emulates the full-fledged TM5-CTM, and constitutes the 'kernel' of TM5-FASST.

The SRCs are stored at the 1°x1° resolution of the native TM5-CTM model (i.e., one 1°x1° SRC map for each of the 56 source regions and for each precursor component) and in principle they can be aggregated into any customized receptor region. One particularly useful aggregation scheme is to combine the receptor grids into the 56 defined source regions; hence the SRCs are stored into 56x56 matrices between identical source and receptor regions. On the other hand, the 1°x1° resolution SRC maps allow the calculation of the resulting concentration in each individual grid point and are therefore useful to create global concentration and impact maps at 1°x1° resolution, or to construct customized receptor regions for studies with specific targets.

The resulting air pollutant concentrations, and their specific spatial distribution, are then further processed into impacts, such as the effect of particulate matter on human health (mortalities, reduction of statistical life expectancy), the impact of O_3 on vegetation and crop damage, the deposition of eutrophying or acidifying components to sensitive ecosystems. Mostly these calculations are based on simple empirical dose-response functions from literature, making use of additional data to be overlaid with the pollutant concentration (or derived metric) in order to properly calculate the exposure (population maps, crops and vegetation maps, sensitive ecosystem maps, etc.).

Table 1 Relevant emitted precursor-pollutant pairs. The number of x's gives a qualitative indication of the most influential precursors (xxx: highest influence). Influences indicated by one x are due to feedback mechanisms affecting the level of oxidants, and hence the lifetime of OH radicals, in the atmosphere, which in turn affects the oxidation rate of the precursors.

Pollutant→ Precursor↓	SO_2 gas	NO_x gas	NH_3 gas	O_3 gas	CH_4 gas	SO_4 pm	NO_3 pm	NH_4 pm	BC pm	POM pm	SOx dep	NOy dep	BC dep
SO_2 (g)	xxx	x	xx	x	x	xxx	xx	x x			xxx		
NO_x (g)	x	xxx	xx	xxx	xx	xx	xxx	x x			x	xxx	
NH_3 (g)	x	x	xxx	x	x	xx	xx	x xx			x		
BC (pm)									xxx				xxx
POM (pm)										x xx			
NMVOC (g)	x	x	x	xxx	xx	x	x	x			x		
CO (g)*				xxx	xx								
CH_4 (g)*	x	x	x	xx	xxx	x	x	x			x		

* From HTAP, 2011

A particular set of impacts are related to the climate impact of short-lived pollutants. A specific set of SRCs has been calculated to evaluate the global radiative forcing resulting from the emitted components. In this case, unlike the pollutant concentrations, the receptor region is

the globe, hence, the SR matrix is a 56x1 array. The global radiative forcings are further processed into other climate-relevant metrics, like equivalent CO_2 emissions and temperature change. The methodologies used for these impact calculations are described in more detail in Section 1.4.

Figure 2 below gives a schematic overview of the TM5-FASST architecture. TM5-FASST is currently implemented as an interactive Excel application (56x56 SR matrices) and as an IDL (Interactive Data Language) programme (56-to-1°x1° grid SR matrices).

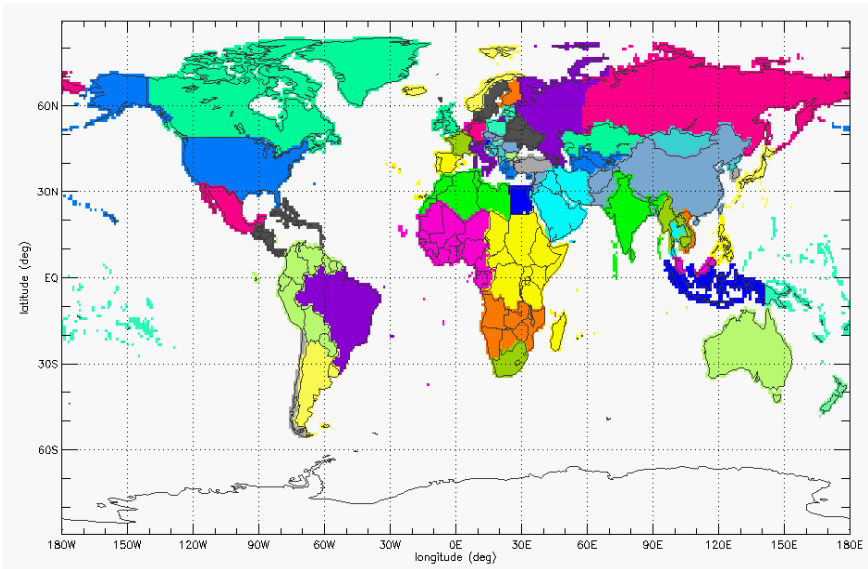

Figure 1 definition of the 56 source regions within TM5-FASST. EU27 is represented by 16 regions.

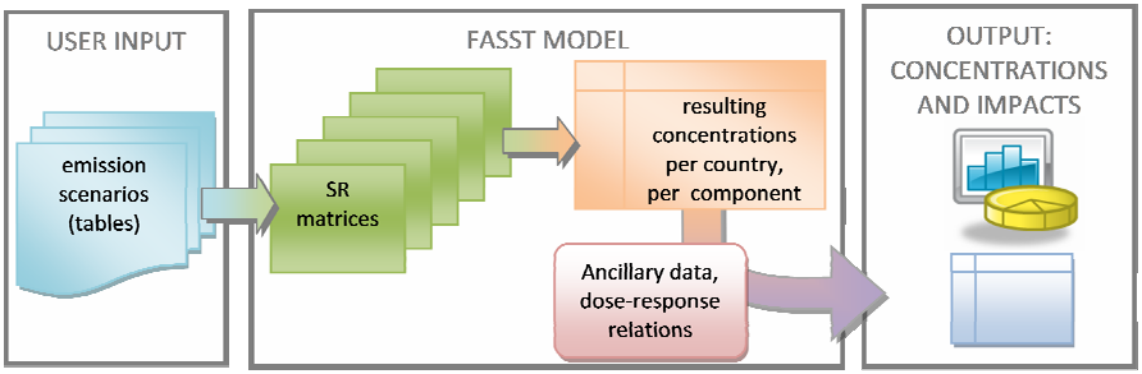

Figure 2 Overview of the major components in the TM5-FASST tool. The traditional process-modeling is replaced by simple matrix calculations.

The performance of TM5-FASST was tested by applying a set of challenging emission scenarios for which previously calculated full TM5-CTM runs were available and comparing the

regionally averaged PM concentrations for both approaches. The applied test scenarios consist of a reference run for 2005 and a low and high emission scenario for 2030. The scenarios were provided as intermediate results in the frame of the Global Energy Assessment by IIASA (Riahi et al., 2012). Table 2 shows the regional relative changes in emissions for the low and high emission scenario compared to the 2005 emission scenario. Emission changes are substantial and exceed in most cases the 20% emission perturbation that was applied for the calculation of the linearized emission-concentration relations. The relative concentration changes between the 2005 scenario on the low/high scenarios are shown in Figure 3 for PM2.5 and for O_3. The concentration responses due to emission changes are generally captured well by TM5-FASST. The PM2.5 responses are slightly underestimated both for increasing and decreasing emissions, and for O_3, the response to decreasing emissions is underestimated, but overestimated to increasing emissions, which is a consequence of the linearization of a non-linear chemical process.

Table 2 Relative changes in emissions by precursor and by region for the low/high test scenarios compared to the 2005 reference scenario, used for the intercomparison between TM5-CTM and TM5-FASST.

Precursor	scenario	Africa	East Asia, SE Asia & Pacific	Latin America & Caribbean	N. America & Europe	South, West & Central Asia
NOX	Low	-23%	-49%	-49%	-71%	-36%
NOX	High	+55%	+57%	+19%	-2%	+193%
SO_2	Low	-39%	-78%	-35%	-85%	-41%
SO_2	High	+149%	+17%	+30%	+11%	+149%
NH_3	Low	+28%	+15%	+42%	+15%	+34%
NH_3	High	+30%	+16%	+42%	+17%	+37%
NMVOC	Low	-24%	-31%	-37%	-45%	-32%
NMVOC	High	+76%	+35%	+14%	-8%	+129%
BC	Low	-27%	-60%	-42%	-69%	-13%
BC	High	+78%	+36%	-13%	-13%	+214%
OC	Low	-22%	-40%	-25%	-27%	-50%
OC	High	+35%	+6%	-20%	-8%	+142%

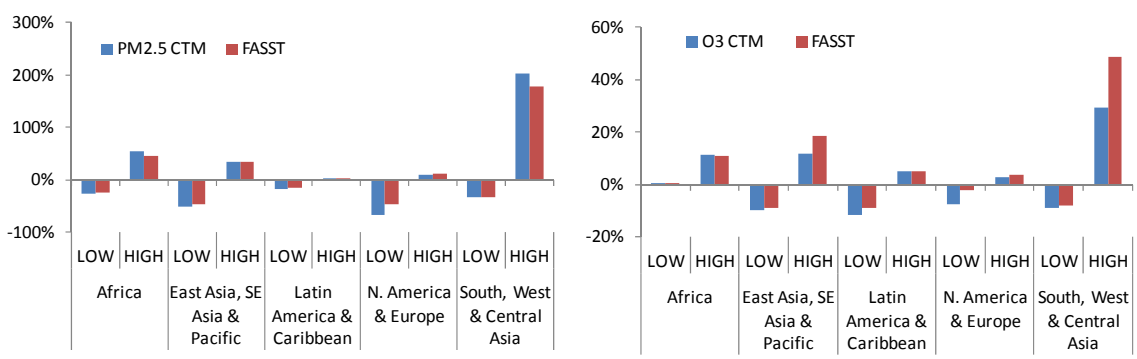

Figure 3 Relative changes in annual mean PM2.5 and O_3 concentration for the high and low emission scenarios changes (year 2030 vs year 2005) listed in Table 2 compared to reference scenario obtained from the full TM5-CTM model and the TM5-FASST linearized model, respectively.

The validity of the TM5-FASST tool has been demonstrated and used in several studies, such as, UNEP synthesis report addressing the control of short-lived climate forcers and co-benefits from climate policy (UNEP, 2011).

1.2 Spatial scaling issues with TM5-FASST

In the current architecture, TM5-FASST takes as input emissions per region (56 regions) without a need for spatial disaggregation to the grid level. It is however important to realize that there is an implicit underlying emission gridding scheme, namely the gridded AR5 year 2000 emissions that were used to calculate the TM5-FASST source-receptor relations. For the year 2000, emissions are spatially distributed in a consistent way with the various contributing SNAP[2] sectors. This implicit spatial distribution is frozen into TM5-FASST and is not dynamically adapted for future scenarios where emissions may possibly be displaced compared to base year 2000. However, the results shown in Figure 3, where the CTM calculations do include a correct spatial gridding for the year 2030 while FASST implicitly uses the 2005 emission gridding, illustrate that the issue is not causing large deviations.

Second, for the specific application in LIMITS, air pollutant emissions are provided by Integrated Assessment Models (IAMs) as aggregated totals over model-specific regions which in general do not match the predefined TM5-FASST 56 regions (see Figure 7). A specific methodology was developed to re-map the IAM emissions to the FASST regions, making use of implicit underlying RCP emission gridmaps. This is described in more detail in section 2.

A third spatial scaling issue refers to the specific problem of air pollution exposure estimates. Using global models for estimating the health impact of atmospheric pollution brings along an additional level of complexity: pollutant concentrations are calculated as the average over the 1°x1° grid-level (roughly corresponding to 100kmx100km) concentration of the model which may not be adequately representing the exposure of population to pollutants like PM and O_3.This will be particularly the case when inside a grid-cell the spatial distribution of emissions and population is inhomogeneous, resulting in sub-grid gradients of concentrations fields and exposure levels which are not captured by the native model resolution. Since generally the highest pollutant concentrations are expected to occur where population density is highest, using grid-averaged pollution concentration values in the TM5-FASST calculations might lead to underestimation of the impacts determined resulting from, for example, population exposure to PM2.5. Ideally, the model should reproduce the concentration metric used for epidemiological studies from which exposure-response functions are derived, namely urban background concentration, rather than regional background or fine-scale and short-term peak concentrations in street canyons (the human body integrates exposure over many years, and people are not always exposed to hotspot concentrations). The next section describes in more detail how this issue is dealt with within TM5-FASST. The methodology is applicable to any gridded output of PM concentrations that is too coarse to accommodate sub-grid exposure gradients.

[2] SNAP: Standard Nomenclature for Air Pollution

1.3 Urban sub-grid parametrization

Previous studies have developed methodologies to calculate the so-called urban increment for some European cities (Amann et al., 2007), but at present no globally applicable simple method is available. Therefore, within TM5-FASST a parameterization was developed to adjust the grid-cell area-averaged PM2.5 concentration to a more appropriate population-averaged urban background concentration, accounting for the sub-grid gradient in population distribution and pollutant concentrations. The urban increment correction will be applied to primary PM only, as secondary PM species (sulfate and nitrate) are formed from chemical conversion mechanisms over larger time and spatial scales, i.e. secondary PM species are expected to be more homogeneously mixed over the native grid-cell. It has to be noted that exposure to O_3 in urban areas will rather be overestimated using the grid-cell average, because of O_3 titration inside traffic-dominated areas. This effect is currently not taken into account in our approach.

In brief, the method relies on high spatial resolution population statistics from which the urban area fraction and urban population fraction inside each native 1°x1° grid-cell are calculated. TM5-FASST has the choice of 2 families of population datasets, listed in Table 3.

Table 3 Population dataset's properties

Name	Source	Metrics used	Resolution	Nr. of sub-grid per TM5 grid-cell	Years available
CIESIN	University of Columbia	Population density Population count	2.5'x2.5'	576	1990, 2000, 2005
UN	United Nations population division	Population count Urban population count	7.5'x7.5'	64	2000, 2005, 2010, 2020, 2030, … , 2100

The CIESIN set has the advantage of very high resolution, but lacks projected data beyond 2005. The UN dataset has a more limited spatial resolution but contains projections until 2100 in decadal steps from 2010 onwards. Further, the UN dataset contains already information on the urban population fraction, whereas the CIESIN dataset provides only count and density, and needs further processing to derive the urban population. The CIESIN dataset was used to label a sub-grid as 'urban' if the population density exceeds 600/km², and 'rural' otherwise. The urban area fraction (f_{UA}) is then the number of urban sub-grids per native grid-cell divided by 576, the total number of sub-grids. The urban population fraction (f_{UP}) is defined as the fraction of the population within the 1°x1° grid-cell which resides in the urban-flagged sub-grids. In the UN dataset, the urban population fraction is directly obtained from 'total urban population' divided by 'total population', summed over the 64 sub-grids of each native grid. The urban area fraction is estimated as the area-weighted average urban population fraction over the 64 sub-grids. This method is less accurate than the CIESIN method and tends to overestimate the urban area fraction and, hence, to smooth out emission and concentration gradients.

The urban increment calculation starts by assuming that black carbon anthropogenic emissions in the native grid-cell (E_{BC} in area A) are divided between the urban and rural areas according to their corresponding population fraction. In this way, it is clear that the fraction f_{UP}*E_{BC} is emitted from area f_{UA}*A and, to ensure mass conservation, the remaining fraction (1- f_{UP})*E_{BC} is emitted from area (1- f_{UA})*A.

Assuming steady-state conditions and neglecting the incoming concentration of BC from neighbouring grid-cells, the 1°x1° grid-average BC concentration can be written as: $C_{BC,1x1} = \frac{E_{BC}}{\lambda}$, with λ the ventilation factor. We assume that this definition of factor λ is also valid for the urban and rural parts of the grid-cell, i.e., it is equivalent with the hypothesis that mixing layer height and wind speed are the same. Hence, the steady-state concentration in the urban sub-area can be written as: $C_{BC} = \frac{f_{UP}}{f_{UA}} \cdot \frac{E_{BC}}{\lambda}$ for the urban contribution and $C_{BC} = \frac{(1-f_{UP})}{(1-f_{UA})} \cdot \frac{E_{BC}}{\lambda}$ for the rural fraction. The ventilation factor λ, including an implicit correction factor for the non-zero background concentration in neighbouring cells, is obtained by taking advantage of the explicitly modelled grid-cell concentration with the chemical transport model (TM5-CTM): $\lambda = \frac{E_{BC}}{C_{BC,TM5}}$. Hence, the urban concentration of BC of a certain grid-cell can be determined by $C_{BC,URB} = \frac{f_{UP}}{f_{UA}} \cdot C_{BC,TM5}$ and the remaining rural fraction by $C_{BC,RUR} = \frac{(1-f_{UP})}{(1-f_{UA})} \cdot C_{BC,TM5}$. In order to avoid potential artificial spikes in urban concentrations when occasionally a very small fraction of the native grid-cell contains a very large fraction of the population, empirical bounds are applied on the adjustment factors:

1) rural primary BC and POM ($C_{eq,RUR}$) should not be lower than 0.5 times the TM5 grid average, and
2) urban primary BC and POM should not exceed the rural concentration by a factor 5.

In any case, the urban and rural adjustments for each of the primary components must fulfil the condition: $f_{UA} \cdot C_{URB} + (1-f_{UA}) \cdot C_{RUR} = C_{TM5}$. The adjusted urban and rural concentrations of the primary emitted components can be cast in one 1°x1° grid population-weighted average value: $C^{pop}_{BC,TM5} = f_{UP} \cdot C_{BC,URB} + (1-f_{UP}) \cdot C_{BC,RUR}$. After replacing $C_{BC,URB}$ and $C_{BC,RUR}$, the population-weighted concentration is expressed as a correction factor to applied on the original 1°x1° area-weighted average concentration: $C^{pop}_{BC,TM5} = \left[\frac{(f_{UP})^2}{f_{UA}} + \frac{(1-f_{UP})^2}{1-f_{UA}} \right] \cdot C^{area}_{BC,TM5}$.

The analogous process is done for primary anthropogenic organic carbon (POM). All secondary components (sulphates, nitrates) and primary natural PM (mineral dust, sea-salt) are assumed to be distributed uniformly over the native 1°x1° grid-cell. In case the native grid-cell size resolution is different from 1°x1°, the PM fields are first interpolated to 1°x1° and the method above described is subsequently applied.

Figure 4 shows the resulting population-weighted correction factor to be applied on the native grid-cell mean primary PM concentrations, as a function of sub-grid urban population fraction and urban area fraction. Obviously the highest correction factor is found when a large fraction of the population is concentrated in a small urban area inside the grid cell, generating a high sub-grid gradient. Conversely, large urban agglomerations where the urban population is covering most of the native grid cell do not lead to a large correction factor. In other words, the correction factor will be highest for spatially limited and isolated urban settlements within rural surroundings.

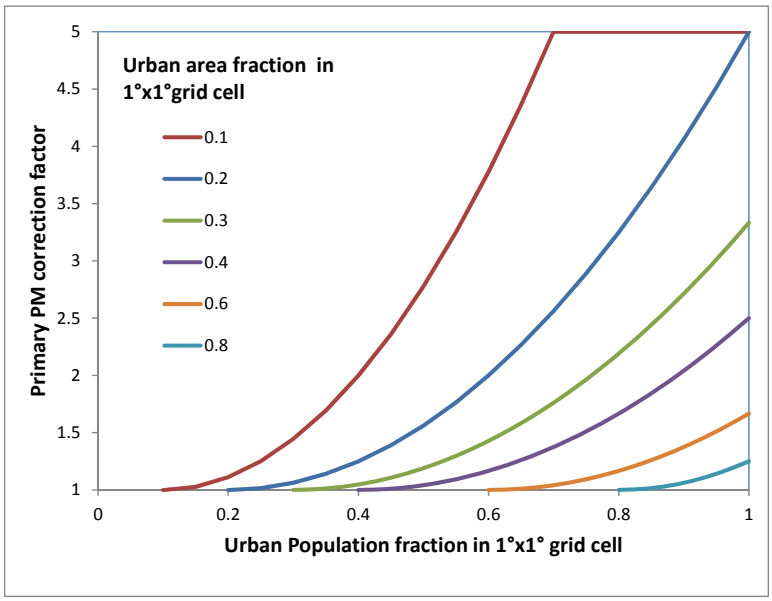

Figure 4 Urban increment correction factor to be applied on grid-average primary PM to obtain the adjusted population-weighted primary PM concentration for the grid cell, as a function of urban population fraction and urban area fraction

This methodology has been validated against a database of urban PM2.5 measurements from national and regional monitoring networks. As the database contains exclusively urban measurements, the adjusted urban PM2.5 was extracted from the corresponding model grids where the measurements are located. Figure 5 shows the median and the inter-90%ile range of individual measurements and corresponding modelled PM2.5 concentrations in North-America, Europa and China. Modelled values (based on the high resolution CIESIN population maps for 2005) are shown both for the urban-increment parameterization and for the non-adjusted grid average. In general, TM5 grid-averaged concentrations (rightmost values) are underestimating the measured concentrations, and the applied parameterization improves the performance of the

model compared to the non-adjusted PM2.5 concentration. Further improvement of this method is currently one of the priorities of the TM5-FASST team. Several possibilities are being explored, such as the use of satellite measurements to conceive a correction factor.

The choice between UN and CIESIN population dataset does not significantly impact on the resulting mortalities, as illustrated in Figure 6. This is due to the fact that primary PM for which the correction is applied constitutes only a fraction of total PM2.5 and the applied exposure-response relations between PM2.5 and mortality number are sub-linear.

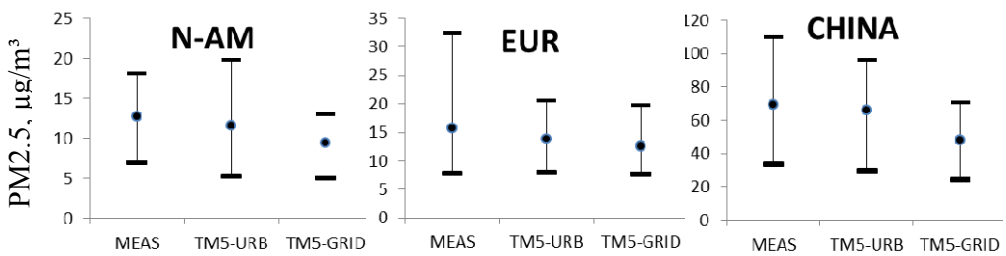

Figure 5 Measured and modelled median (5%ile, 95%ile) urban PM2.5 concentrations in North America (left), Europe (middle) and China (right). Measurements are from routine monitoring programs. TM5-URB values include the urban increment correction described in the text, and TM5-GRID refers to the unadjusted grid-cell average PM2.5 concentrations.

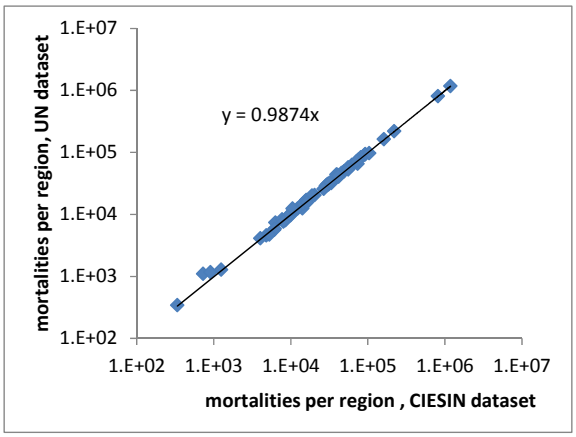

Figure 6 Total mortalities per FASST region for base year 2005, after applying the urban increment correction, using two sets of population maps (UN, CIESIN)

1.4 Impact calculation

The TM5-FASST tool is used to determine, among others, impacts of air pollution on human health, vegetation and radiative forcing. Within the context of the LIMITS project these are the impacts analysed and the used methodologies will be briefly described and documented in the following section. In general, the methodology involves the combination of pollutant concentration fields with appropriate population or vegetation exposure – response functions for health and ecosystem – from which it is possible to determine the (avoided or not) premature mortality and

crop loss. Response functions for human health and crops are taken from literature. Furthermore, instantaneous radiative forcing and related common climate metrics (CO_2eq of short-lived pollutants) are evaluated as well based on published literature.

Health impacts

Ground-level concentrations of ozone and PM2.5 are associated with cardiovascular and respiratory mortality (e.g., Jerrett et al. 2009; Krewski et al. 2009, WHO, 2013). The 2009 report of the World Health Organization estimated that particulate matter exposure causes about 8% of lung cancer deaths, 5% of cardiopulmonary deaths and about 3% of respiratory infection deaths, which is about 1.15 million deaths each year (WHO, 2009). On the other hand, a later study by Anenberg et al. (2010) estimated that global mortalities due to respiratory illness caused by O_3 were about 0.7 million and population exposure to PM2.5 resulted in about 3.5 million cardiopulmonary and 0.2 million lung cancer mortalities. In TM5-FASST the methodology described in the latter study, as well as a more recent revision of the exposure functions by Lim et al. (2013) and Burnett et al. (2013) are applied to determine the avoided premature mortalities for a population older than 30 years exposed to PM2.5 and O_3. Population numbers (age fractions and totals) are obtained from the UN Population Division (UN, 2011). Cause-specific mortalities from ischemic heart disease, chronic obstructive pulmonary disease, acute lower respiratory illness diseases and lung cancer are calculated with functions provided in Burnett et al. (2013) as impact to PM2.5 exposure. In the case of exposure to O_3 only mortalities from respiratory disease are considered applying the risk rate from Jerett et al. (2009) to functions described in Anenberg et al. (2010). Cause-specific base mortalities for the year 2005 are taken from the most recent WHO ICD-10 update (WHO, 2012) for individual countries where available, or back-calculated from 14 WHO regional average mortalities when not available.

Impacts on crop yields

Ozone is a toxic compound to plants with considerable negative effects on leaf health, growth and productivity of crops, trees and other plants, affecting the vegetation composition and diversity (e.g., Fuhrer and Achermann, 1994; Jager et al., 1996; Fuhrer, 2009). In fact, O_3 is one of the main air pollutants that reduces crop yields leading to the loss of large amount of wheat, maize and rice (UNEP/WMO, 2011). This loss is not only important in regard to damage in ecosystem but will result in large economy losses and is a threat to food security. The O_3 damage on crops and vegetation with its impact on yield loss is also estimated with TM5-FASST. The methodology applied in TM5-FASST to calculate the impacts on 4 crops (wheat, maize, rice and soy bean) is based on Van Dingenen et al. (2009). In brief, as it was done for the pollutants, the SR-relations for various metrics for crop exposure to ozone (AOT40 and mean seasonal daytime ozone concentration) were pre-calculated based on stored hourly ozone concentrations from the full TM5 model runs. Country or region-averaged values for the O_3 metrics are obtained by averaging or accumulating over the appropriate crop growing area (which varies by crop and geographical location) the SR coefficients and overlaying those with crop suitability maps from Fischer et al. (2000). Whereas in Van Dingenen et al (2009) crop growing season data were obtained from various sources, we recently updated this part of the data by retrieving globally gridded growing season information as well as geographical crop distribution from the Global Agro-Ecological Zones project (GAeZ, http://www.fao.org/nr/gaez/en/). The relative yield loss for

each crop is then obtained by applying appropriate exposure-response functions to the region-averaged exposure metric. Currently only 4 crop types are included in the analysis due to limitations on data availability. However, Hollaway et al. (2012) has determined the intercontinental transboundary contributions to crop ozone exposure and subsequent yield reductions in the Northern Hemisphere for 6 major agricultural crop types: wheat, rice, maize, soybean, cotton and potato and GAeZ now also provides growing season maps for many additional crops. Therefore, the possibility of including additional crops in the TM5-FASST calculations is currently being explored.

Climate impacts of short-lived pollutants

Usually when dealing with climate change the main species considered for the radiative balance are greenhouse gases which have a long lifetime. However, short lived species (i.e., common air pollutants) also contribute for climate change, both directly and indirectly.

TM5-FASST makes use of TM5 pre-calculated gridded forcing efficiencies per unit column-integrated species mass over each 1°x1° grid-cell. The forcings were obtained with the off-line radiative transfer model OTM (Marmer et al., 2007). Global instantaneous forcings per Tg of emitted component are calculated for each source region and each emitted component to be then used into TM5-FASST. Similar calculations were done for ozone but using the forcings obtained for the scenario results by Dentener et al. (2005), based on Edwards and Slingo (2006). The normalized forcings from a reference scenario calculated with TM5-CTM are stored and are subsequently scaled with aerosol and ozone columns from actual scenarios. With this emission based data is then possible to calculate the corresponding GWP and GTP for short lived climate forcers. The equivalent CO_2 emissions (CO_2eq) are used as climate-relevant metric for the emitted short-lived pollutants following the methodology Fuglestvedt et al. (2010). For each emitted component the instantaneous forcing of a 1 year pulse emission is integrated over a time horizon of 20, 100 or 500 years, and the 1 year CO_2 emission strength that would yield the same integrated forcing is calculated. The integrated forcing is calculated for primary PM2.5 emissions (BC, OC), for secondary aerosol precursors (SO_2, NOx, NH_3) and for O_3 precursors (NOx, CO, NMVOC, CH_4). Only direct radiative forcing was considered, indirect effects on cloud formation and lifetime are not included.

2. TM5-FASST within the LIMITS project

As its name says, the TM5-FASST model is a tool used to quickly screen impacts resulting from emission scenarios. This tool is quite useful for its swiftness in providing global results for a large set of input scenarios. It provides a general overview of impact on human health and vegetation allowing for optimization of policy scenarios. Furthermore, impact analysis can be done by region or sector to individualize contributions to ground-level pollution.

The model is being used in the framework of the LIMITS project, assessing the co-benefits of combined climate and air pollution strategies in long-term integrated assessment scenarios where both climate mitigation and air quality policy are represented in detail.

2.1 The IAMs in LIMITS

GCAM (Global Change Assessment Model) explores the complex relationship between economic activity, energy systems, land use systems, ecosystems, emissions and resulting impact on climate change. The main focus of this model is technology analysis and implications of various technology pathways for climate policies in a national and global context. The model includes 16 emissions tracked (e.g., CO_2, CH_4, N_2O, and SO_2), is divided into 14 regions and runs from 1990 to 2095 in time steps of 5 years. The model assumes that regional population and labor productivity growth assumptions are the main drivers for energy and land-use systems. The end-use energy service demands associated with time path of economic activity have been aggregated as three energy services: industrial, building, and transportation. MAGICC is an embedded reduced form model of the carbon cycle, atmospheric chemistry and climate change that provides GHG concentrations, radiative forcing, and climate change. This is the only non-European model participating in the LIMITS project and further information on its specifications can be found in Calvin et al. (2011).

IMAGE (Integrated Assessment Modelling Framework) is in fact a complex modelling framework, i.e., several linked and integrated models describing long-term dynamics of global environmental variations, such as air pollution, climate change, and land-use change. The TIMER is the global energy model that describes the demand and production of primary and secondary energy and the related emissions of GHGs and regional air pollutants. The Land-Use Emissions Model (LUEM) computes the emissions of atmospheric pollutants (GHGs and air pollutants) from both natural and land-use related sources. The model provides results for 16 global regions. A detailed description of IMAGE can be found at Bouwman et al. (2006).

The MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) model, version V, is a linear programming system engineering optimization model used for medium- to long-term energy system planning and policy analysis. The model minimizes total discounted energy system costs, and provides information on the utilization not only of several energy and technology related variables (from use to trade) but also on pollutant emissions. The model also includes generic representations of agriculture and forestry, including emissions and mitigation options for the GHGs and other radiatively active substances. The model includes 11 regions across the globe and provides results for the time period of 2100. Further information can be found at Messner and Strubegger (1999), and Rao and Riahi (2006).

REMIND (Regionalized Model of Investments and Development) is a global multi-region model that represents an inter-temporal energy-economy-environment. It incorporates the economy, the climate system and a detailed representation of the energy sector, maximizing global welfare based on nested regional macro-economic production functions. This model allows for unrestricted inter-temporal trade relations and capital movements between 11 world regions, providing information regarding technology options and policy proposals for climate mitigation. Mitigation costs estimates are based on technological opportunities and constraints in the development of new energy technologies. Further information can be found at Leimbach et al. (2010).

The WITCH (World Induced Technical Change Hybrid model) regional model allows for the analysis of the socio-economic dimensions of climate change. It provides figures of the economic

consequences of climate policies and helps to devise optimal strategy planning for climate change mitigation. In this model the non-cooperative nature of international relationships is explicitly accounted for and climate policies across the 13 regions included and over time can be differentiated allowing considering several policy scenarios. The model most interesting features regard the endogenous treatment of technological innovation in the mitigation sector, and the modelling of multiple externalities, both climatic and technological, in a game-theoretic setup. The climate module provides information on climate change impact and optimal adaptation response. Further details on the model can be found at Bosetti et al. (2006, 2009).

2.2 Regional emissions downscaling: the interface of model output to TM5-FASST input

As described in the previous section each of the models has a different number of native regions ranging from 11 to 26 (see Figure 7). On the other hand, TM5-FASST tool considers 56 regions (Figure 1). A distribution based on country area alone would lead to biased values so it was necessary to develop a method that would allow the conversion of LIMITS model regional data into FASST regional input. In brief, the method consists of using available gridded RCP emission maps to spatially distribute the region-aggregated IAM emissions, and to re-aggregate them into the FASST regions.

Prior to the conversion it was important to determine which countries were included in each of the model regions and how these could compare to the TM5-FASST regions. The world country list reference and gridded country codes were obtained from CIESIN data. The model regional emission data was converted into country emissions so that these values could later be used into the 56 TM5-FASST region definitions. For this task a tool written in IDL was created. The output from the IAMs available at the LIMITS database consisted of emissions for several air pollutants and GHGs, for each of the model regions, for 12 scenarios, for 15 years (every 5 years from 2005 to 2050 and then every 10 years until 2100), and for different sectors including energy demand and supply, land use, solvents and waste (approximately 17 depending on compound). This data is stored in an Excel file that is read with the IDL code and output is written in files that can be used in the emission tables of the Excel interface of TM5-FASST but also read as input in the coded version that performs grid based calculations. To convert regional emission values of each model (for one year, one sector, and one scenario) into values per country it is necessary to make use of a weighting factor (λ). The RCP gridded emission data is arranged (per year, per sector, per pollutant) into country emission values ($E_{RCP(country)}$) making use of the CIESIN country code map. These values are then summed-up into region values according to the regional definition of each model ($E_{RCP(region)}$). Weighting factors for each country can then be determined based on the fraction of the country emissions in regard to the regional total:

$$\lambda_i = \frac{E_{RCPi}}{E_{RCP(region)}} \text{ for a country } i.$$

In this way it was possible to disaggregate the regional emissions of the IAMs ($E_{mod,reg}$) into country values ($E_{mod,i}$) that were re-grouped into regional values according to TM5-FASST definition (E_{FASST}):

$$E_{FASSTreg} = \sum_i (E_{\mathrm{mod}\,i}) = \sum_i (E_{\mathrm{mod}\,reg} * \lambda_i) \,.$$

It is important to note that this algorithm is used to assign in a consistent way (both spatially and sector-wise) the IAM emission quantities to FASST regions. However, as stated above, FASST does nor inherit the underlying gridding for the respective RCP scenario years, as it uses the frozen year 2000 gridding. In the future it will be important to understand what uncertainties are introduced by this approach, namely the representativeness of RCP air pollutants emissions that are used as reference for redistribution, and what are improved methods can be applied to perform this conversion.

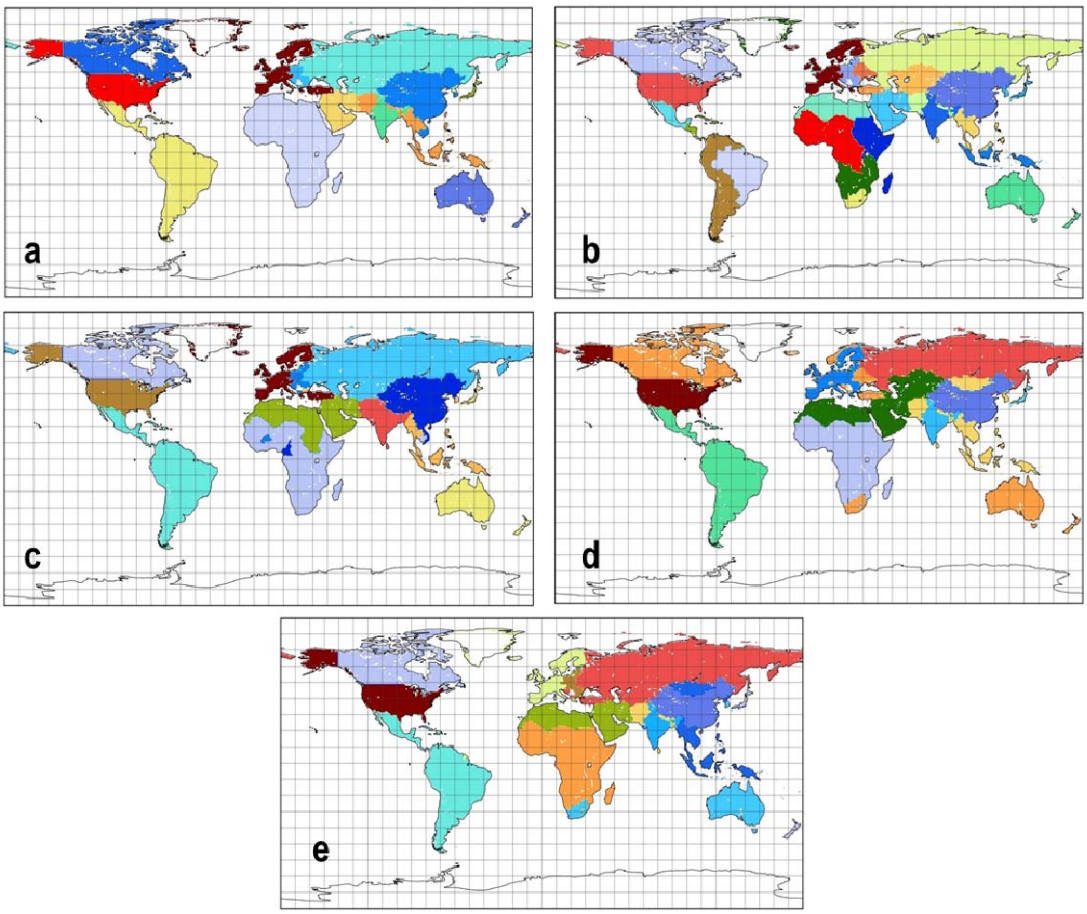

Figure 7 Native regions for 5 IAMs: a) GCAM, b) IMAGE, c) MESSAGE, d) REMIND, and e) WITCH. (see detailed description of models in Section 3)

3. Impact calculation in the LIMITS context

The Work Package 4 of the LIMITS project focuses on the analysis of benefits and trade-offs from climate change mitigation strategies towards the 2° objective. As the current climate change and air pollution policies do not usually account for the inter-linkage between the two phenomena, here the objective is to illustrate that these should not be dealt with as conflicting goals but abatement actions can rather be applied as synergistic process.

The first stage of the project consisted in developing a set of scenarios including different climate mitigation measures and targets. At this stage, scenarios were developed combining the former with air pollution policy targets, i.e., an integrate climate-pollution scenario. In this report it will be shown how the source-receptor model TM5-FASST allows for the identification of effective measures that can be both cost-effective and towards the reduction of negative impacts on human health and vegetation exposure.

3.1 Scenarios

The protocol of air pollution scenarios includes three alternatives for future global air pollution legislation, assuming different emission factors for a number of air pollutants by sector and region. These are mostly focused on non-climate policies and control measures for emissions of air pollutants, such as PM2.5, NOx and SO_2. Still, the scenarios were applied to the existing baseline scenario from WP1 (LIMITS1) and the 2.8 W/m^2 stringent climate policy scenario (LIMITS6). With this analysis it will be possible to study the impact of alternate air pollution control assumptions on pollutant emission trajectories out to 2030 and 2050. The time-varying energy system structures and long-term climate targets are kept and the models will just add the representation of air pollution control actions.

The three sets of scenarios are as follows:

1. CLE: “continued legislation” is a ‘business-as-usual’ scenario assuming that existing and planned environmental legislation until 2030 is efficiently put into practice with adequate institutional support.

2. FLE: “fixed legislation” is more a hypothetical case if in terms of legislation nothing changes from what was implemented in 2005, i.e., measures are ‘frozen’ but emissions evolve according to regional development and, therefore, with serious deterioration of air quality. This scenario is used as a proxy for a world of ‘failed’ emissions controls, where institutional and political barriers lead to non-implementation of planned legislation.

3. SLE: “stringent legislation” assumes implementation of ‘best available technology’ reflecting assumptions on improvements in institutional structures to support a high level of air pollution control globally. This would be the case with increasing environmental awareness that leads to improvements in the speed and effectiveness of pollution control beyond what is currently legislated.

The comparison between the frozen and continued legislation scenarios might provide an indication of the efficacy of current air quality legislation across different regions. On the other hand, the analysis of the SLE scenario will give insight regarding the efficacy of increased stringency in air quality legislation beyond what is currently legislated. The LIMITS6 variants can then be used to determine the extent of co-benefits in terms of pollution reductions in 2030 and 2050 that can be achieved from a long-term climate policy.

The emission factors for energy-related combustion (supply and demand), conversion, and transformation sectors are based on the GAINS model and include recent developments in the air pollution community, in particular the Task Force on Hemispheric Transport of Air Pollution (TF HTAP) as well as various parallel on-going EU funded initiatives. In this way it was possible to ensure overall reliability, comparability and credibility. These trajectories have been derived based on the 2011 World Energy Outlook (http://www.worldenergyoutlook.org/publications/weo-2011/) baseline scenario implemented in the GAINS model. Data is provided in multi-country world regions based on the resolution of 26 world regions that are later adapted into the region definition of each model. Emissions included are SO_2, NOx, OC, BC, CO, and NMVOC.

3.2 Results

The 5 IAM models considered provided a global emission dataset for different scenarios considering different stages of air pollution and climate policy implementation. These were used as input of the TM5-FASST to determine the air pollution impacts. The analysis of these results is still at a very initial stage within the LIMITS project. Still, as example of the potential of the TM5-FASST tool it is possible to see in Figure 8 some initial results of the analysis of data. The total number of premature mortalities, amount of crop loss and additional contribution of short-lived species and CH_4 for global CO_2eq values were estimated as a result of the 2030 pollutants' emissions. For this exercise only four scenarios were considered: current and stringent air quality legislation (CLE and SLE, respectively), combined or not with climate policy (LIMITS6 and 1, respectively). Hence, it is possible to identify the impact of different policy implementation that aims at reducing air pollutants and/or GHGs emissions.

The results show a clear positive impact of stringent air pollution legislation (SLE) with decrease of premature mortalities and crop loss and radiative forcing. The combination of such strategies with climate policy brings, as expected, additional beneficial results with higher reduction of the impact on population and vegetation. However, the radiative forcing caused by short-lived species is, in LIMITS6 CLE and SLE scenarios, higher than LIMITS1 scenarios for the IMAGE, MESSAGE and WITCH models. This increase in CO_2eq values is related to the emissions of certain air pollutants which are higher in LIMITS6 scenarios, such as, for example, BC for MESSAGE. Still, as these results are preliminary further detailed analysis is necessary to fully understand these changes.

The TM5-FASST is also an ideal tool to ascertain the variation of impacts resulting from the change in emissions, using one year and/or scenario as reference. Furthermore, also a sector

analysis is possible when data are provided in such basis. This work will be actively developed in the LIMITS project to understand the effect from emission trends and identify best policy scenarios.

4. Summary

The TM5-FASST model allows for the internally consistent determination of co-benefits of joined air quality and climate policy and provides the possibility to evaluate the trade-offs of different future scenarios. This tool has been successfully adapted to be used within the LIMITS project and a platform has been built to disaggregate emission data provided by native model regions into the 56 regions considered in TM5-FASST.

In the present document several improvements that have been recently made to this model were described. These include the update of data and functions used to determine the health and vegetation impact resulting from air pollution exposure. Additionally, more focused on spatial downscaling, the implementation of the sub-grid parameterization is introduced. This urban increment is applied to primary PM and adjusts the grid-cell area-averaged concentration to a more appropriate population-averaged urban background concentration.

As mentioned above, the methodology employed adapts the coarser regional emission data into higher resolved 56 TM5-FASST regions. The effect on the results from this disaggregation still has to be analysed in detail. Currently this is a necessary step because the source-receptor relations used in the impact calculation are only available for TM5-FASST regions. In the future it will also be explored the possibility of recalculating the source-receptor factors according to the different model regions. In this way, it might be possible to avoid artificial features caused by the post-modelling disaggregation of emissions. Yet, this will obviously hamper a detailed regional analysis, which, using the TM5-FASST regions provides results for many individual countries.

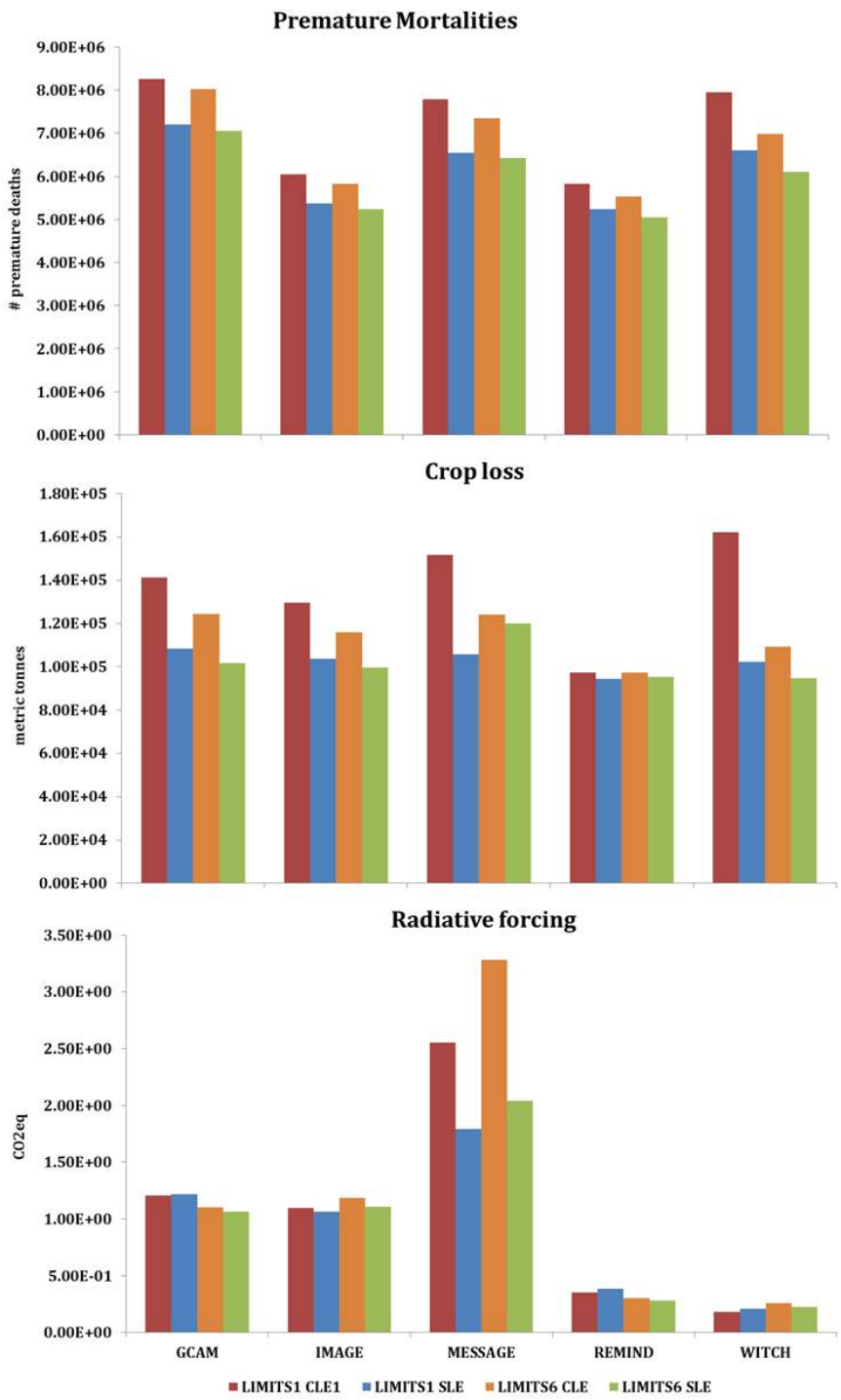

Figure 8 Impacts calculated with TM5-FASST with the emissions provided by 5 IAMs (GCAM, IMAGE, MESSAGE, REMIND, WITCH) for 4 different scenarios (see description above in Section 3.1): premature mortality (top), crop loss (middle), and radiative forcing (bottom).

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