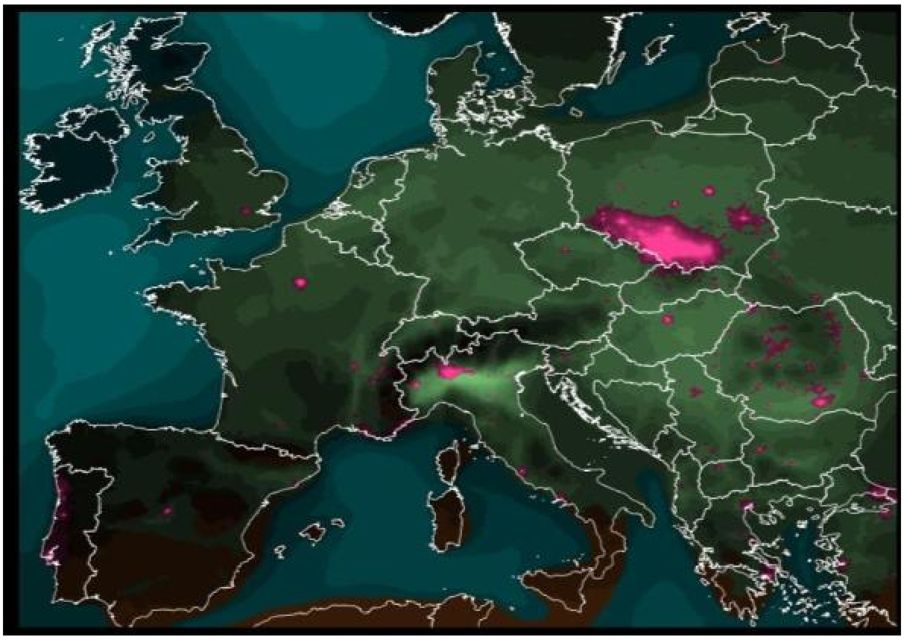
Existing data and knowledge gaps about air-climate inter-linkages and way forwards for improvement



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European Topic Centre on Air Pollution and Climate Change Mitigation

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Front page picture
Typology of aerosol dominating the PM10 mix (pink: primary anthropogenic, green: secondary, blue: sea-salt, brown: desert dust) modelled by INERIS with the CHIMERE model for the winter of 2009. This picture highlights the need to account for the secondary fraction of aerosol when deriving impacts from primary emission projections.

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Contents

1 Introduction

1.1 Scope

The knowledge base on air-climate interactions is growing, especially with increasing interest created by activities of the IPCC, IGBP/IGAC, EU research projects and the recognition of the role of short lived climate forcers under LRTAP and the UNEP BC assessment, development of a 2030 framework for EU climate and energy policies, and not to forget activities under the former ETC/ACM consortium (2010-2013). It is therefore important that EEA maintains and expands its understanding of the drivers of atmospheric change, their interaction, and the resulting changes in atmospheric composition, as well as their impact on human health and ecosystems in order to share this information with the EEA member countries and the European Union institutes.

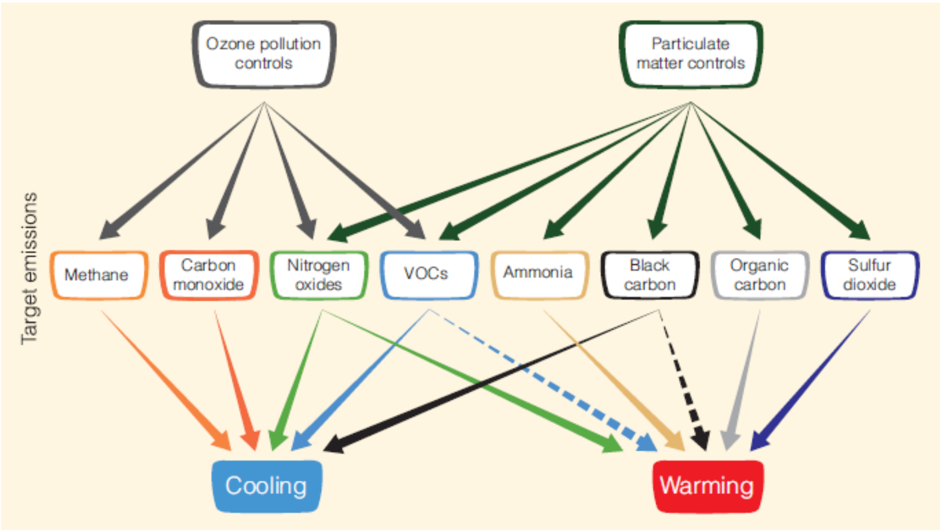

Figure 1: ***Schematic diagram of the impact of air pollution emission controls and climate impacts. Solid black lines indicates known impacts, dashed lines indicates uncertain impacts (IPCC AR5, Chapter 8, FAQ 8.2)***

Over the past years progress has been made in understanding the linkage between air pollution with climate change (Figure 1). For example, it became clear how air pollutants contribute to climate forcing (enhancing or decreasing it) and how they affect precipitation patterns through indirect radiative forcing (IPCC, 2013). Koren et al (2014) have recently shown that even small amounts of aerosols can affect the number and size of clouds. At the same time climate change can lead to changing distribution patterns of air pollutants (Jacob and Winner, 2009), and reforestation (often seen as a climate change mitigation measure) can be a cost-effective abatement measure for ground-level ozone and nitrogen oxide (Kroeger et al, 2014). And we need to keep in mind that reductions in air pollutants/SLCPs can delay global warming and as such be useful to help society and environment to adapt to climate change. But it cannot prevent a substantially greater warming in the longer term. In other words, reducing the emissions of CO_2 and other well-mixed GHGs remains needed to keep the global temperature increase within the 2°C target (see also Solomon et al, 2013).
Using data available from, and in collaboration with, current integrated assessment models and activities such as GAINS (IIASA), FASST (JRC), IMAGE (PBL), and results from EU research projects (e.g. Pegasos) and ETC/ACM studies, the **purpose of the present document is to identify the main data and knowledge gaps on air-climate interlinkages and propose how to close this information gap in the coming years through collaboration activities and future targeted assessment studies**.
This with a focus on information concerning Europe and the EEA member countries and on the following three topics:

(i) Emission scenarios: completeness of scenarios in terms of coverage of both air pollutants and greenhouse gases and availability of AP and GHG scenarios that consider a variation of climate change policies, both for the time frame present day-2050.

(ii) Climate impact: support the decision on the most appropriate indicator (RF, ERF, GTP or GWP, absolute or relative) and secure availability of the relevant indicator for all compounds at the geographical and temporal scale selected.

(iii) Health and ecosystems impacts: Unlike climate impacts, there are no simple transfer function that can provide impacts of a given emission reduction measure. The only options are (1) emission response models (FASST, GAINS, SNAP) or (2) full frame chemistry transport models. A review of the strengths and weaknesses of each approach will be performed including assessment of availability of the models, required input data and expected outcomes in terms of health and ecosystem impacts.

While the section on emission scenarios (2) will put and emphasis on the synergies between air quality and climate measures, the subsequent sections (3 on climate impacts and 4 on health & ecosystems) will be focused on either one or the other.

1.2 State of the art

Assessing the combined impacts of various social and economical projections or environmental policies on climate and air quality is classically referred to as integrated assessment modelling.

Suite of models (see Annex I for short descriptions of such models) are used to develop scenario and assess multiple impacts, some examples:

- Social-economic models that are used to provide the input for the demographical and economic changes foreseen. Some examples are GEM-E3, Worldscan, MERGE, Witch, ENV-linkages.
- Sectoral models such as TREMOVE (transport sector), CAPRI, MAGNET (Agricultural sector), PRIMES (energy sector) and/or specific model such as GTAP (international trade).
- Models that are used to generate emissions from the economic activities, some examples are POLES, PRIMES, GAINS, TIMER.
- Models that are used to calculate concentrations/impact from the estimated emissions, these models include chemistry transport models such as TM5, EMEP, CHIMERE, or surrogate models such as FASST, IMAGE, GAINS.
- Models that are used to calculate the change in climatic parameters due to a change of GHG and air pollutant concentration, i.e. global coupled general circulation models (Hadley, IPSL, ECHAM).
- A few models are integrated over the whole chain; examples for these types of models are GAINS and IMAGE.

Models differ in spatial and temporal scales considered, and in the complexity of the simulation undertaken. Complexity can differ in number of economic sectors handled, spatial resolution, time horizon, emissions, impact calculated and technology (options) available. For models focusing on just one of the component of the chain listed above, feedbacks are often a weak point.

Introducing stringent measures in a certain sector or region will have an economic impact and create structural changes. When, for example, an energy tax is increased, the consumer will be motivated to invest in energy-saving options (through substitution or behavioural changes) as a result, the share of energy use in our economic system will be reduced. The more complex scenarios use a series of models to estimate the parameters including sensitivity runs or ensemble means of a series of comparable models (Figure 2).

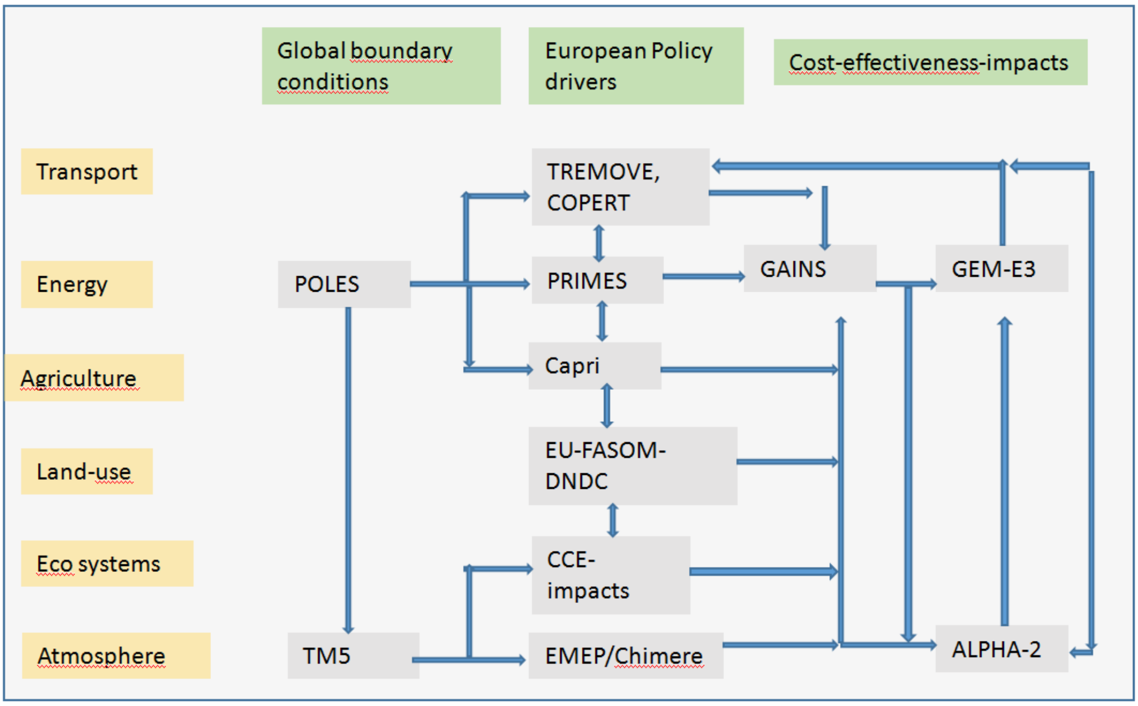

Figure 2: Suite of models describing the DPSIR chain for the TSAP scenarios (IIASA, 2014).

Integrated Assessment Modelling is a complex topic that has been the focus of substantial scientific work in the past couple of decades. If some of the existing tools already offer the possibility to assess air and climate interlinkages, others are limited to a few (emission related) indicators. **The present report will review the capacities of available tools to assess the air climate interlinkages. In order to point out possible ways forward we will emphasise if bottlenecks can be attributed to current knowledge gaps or missing input data**.

2 Emission scenarios

Emission scenarios classically include two components: a representation of a reference situation (that can be an actual emission inventory reported for a recent period) and a quantification of possible or plausible future pathways. These two components are introduced in the two subsections of the present chapter.

2.1 Emission projections

In this report a number of scenarios and models have been selected to assess the current state of play in climate-change-air quality inter linkages. In the next paragraph (2.1.1) the selection criteria that have been applied in selecting these scenarios are presented. In paragraph 2.1.2 the selected scenarios are presented in order to point out some general notes on the state of play and possible improvement in the representation air-climate inter linkages at the end of this chapter (2.3.1).

2.1.1 Selection of scenarios

An initial set of criteria was developed and tested through a number of interviews with ETC/ACM experts in the field of air and climate (see interviews in Annex 1). The scenarios to be selected comply with most of the following requirements:

1. Have link with climate change and air quality policies;
2. Be recent (preferably developed after 2010);
3. Include different policy/decision making levels (EU, OECD, National);
4. Include a scenario with a focus on air quality strategies with climate change baseline and a scenario with a focus on climate change polices with air quality baseline;
5. Include a scenario focussing on European countries and a scenario focussing on the EU as part of a global assessment;
6. GHG and AP emissions should be available in the scenarios;
7. Beside End-of-Pipe (EOP) and CO_2 reduction options, some scenarios should also include measures of the type that involve structural changes, consumer behaviour, energy/transport designs, food systems, etc.
8. Include wide ranging of scenarios (baseline, extreme/exploration, business as usual /current/best policies) that include an own story line, economic-social trend developments and various variants.

Taking note of the above given criteria, in the ETC/ACM expert's opinion, the most important scenarios to consider were TSAP (from an air quality, European perspective) and the RCP scenarios (from a climate, global perspective, including follow-up studies such as EC-LIMITS, ECLIPSE, PEGASOS, CCMI, IC-IMAGES). The present report will focus on these two priority scenarios although there are possible additional scenarios that could comply with the selection criteria listed above. The Global Energy Assessment has developed energy projection pathways that comply with the RCP storylines and take into account air pollution policies, including a quantification of the associated costs. A scenario that studied especially economic interactions and could be of interest as an economic background scenario is the long-term growth scenario (up to 2060) from the OECD (OECD, 2013). Other scenario that were mentioned, but not yet fully reported is UNEP that prepares a new scenario based on GEO-5 with as important new aspects the flow of materials and more focused on LCA contributions. The models used to develop such scenarios, and possible alternative tools are presented in Annex II.

2.1.2 Short description of the TSAP and RCP scenarios.

2.1.2.1 <u>TSAP scenario</u>

The Thematic Strategy on Air Pollution (TSAP) –established in 2005- has been revised multiple times over recent years (see details http://gains.iiasa.ac.at/TSAP). The overall objective, however, remained the same, i.e. to explore how the European Union could make further progress in achieving levels of air quality that do not give rise to significant negative impacts on, and risks to human health and environment' (EEA, 2013, IIASA, 2013). All detailed data of the TSAP scenarios can be retrieved from the GAINS-online model (http://gains.iiasa.ac.at/gains/EUN/index.login?logout=1). The final TSAP 2013 Baseline employs the projection of economic activities (e.g., energy use, transport, agricultural production, etc.) that has been developed for the Commission Communication on 'A policy framework for climate and energy in the period from 2020 to 2030' (EC 2014a). It includes PRIMES2013 Reference Energy scenario. The CAPRI model has been used to project future agricultural activities in Europe consistently with the macro-economic assumptions of the PRIMES-2013 Reference scenario and considering the likely impacts of the most recent agricultural policies.

The following GHG emissions are available in the GAINS-online tool: CO_2, CH_4, N_2O and F-gases. For CO_2, regulations are included in the PRIMES calculations as they affect the structure and volumes of energy consumption. For non-CO_2 greenhouse gases and air pollutants, EU and Member States have issued a wide body of legislation that limits emissions from specific sources, or have indirect impacts on emissions through affecting activity rates. The effect of these legislations have been assessed through bilateral consultations with the EU member states. For the Commission proposal on the Clean Air Policy package the current legislation for CH_4 emissions that is assumed in the GAINS baseline projection is used.

The following air pollutant emissions are available in TSAP: SO_2, NOx, $PM_{2.5}$, NH_3, VOC, BC, OC, TSP.

In order to explore future European air quality, the TSAP emissions scenarios needs to be refined. In particular, the data must be distributed on a spatial grid and available for a minimum set of chemical species (pollutants and their precursors). The TSAP emission data were therefore further processed, to allow air quality modelling, in the Eclipse FP7[1] project. They were delivered in May 2013. A more detailed review of the ECLIPSE scenario can be found in EEA, 2013b.

2.1.2.2 RCP scenarios

To support the assessment of the IPCC report various sets of scenarios have been developed over time (IPCC, 2013). The most recent are called the RCP (representative concentration pathways) scenarios. (Moss et al., 2010; Van Vuuren et al., 2011a). These scenarios form the basis of the current generation of climate model runs as part of the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP, Lamarque et al., 2013) and Coupled Model Intercomparison Project (CMIP5, Taylor et al., 2012). The RCP set consists of four scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) each of which describes a different trajectory for emissions of long-lived greenhouse gases (LLGHGs) and short-lived air pollutants, the corresponding concentration levels, land use and radiative forcing. Together the four RCPs span a range of possible climate forcings varying from 2.6 W/m^2 to 8.5 W/m^2 in 2100 (Van Vuuren et al., 2011a). It should be noted that the four RCPs have been produced by four different (see Table 1) integrated assessment models (see Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; Van Vuuren et al., 2011b, Colette et al., 2012).

For Europe, the RCP2.6 and 4.5 scenario's leads to an almost 80% and 20% reduction of GHG emissions by 2050, while in the RCP6.0 and RCP8.5 scenarios the GHG emissions actually increase for Europe. The emissions trajectories of air pollutants are determined by three important factors: the level of economic activities, the assumed degree of air pollution control and the assumed level of climate policy (Van Vuuren et al., 2011a). In the RCPs, all modelling teams assumed that higher income levels lead to the implementation of more stringent air pollution control measures. Overall, this implies that in each RCP air pollutant emission factors gradually decline during the course of the century. In the Representative Concentration Pathways (RCP) database (RCP Database, 2009), emissions concentrations and land-cover change projections and radiative forcing are documented. Information on individual RCPs (RCP2.6, RCP 4.5, RCP 6.0 and RCP 8.5, see Table 1) is provided. Version 2.0 of the database includes harmonized and consolidated data for three of the four RCPs (RCP, 2009). Results of the model runs can be compared by using the RCP webtool. Sectoral

[1] http://eclipse.nilu.no/

emissions for greenhouse gases and air pollutants[2] are available on a global regional scale for the period 2000 – 2100 and also gridded information (0.5 x 0.5 global grid) is provided.

Table 1: Overview of models used in the development of RCP scenarios.

RCP	Organisation	Model
2.6	PBL Netherlands environmental Assessment Agency	IMAGE
4.5	Northwest National Laboratory's Joint Global Change Research Institute (JGCRI)	MiniCAM
6.0	National Institute for Environmental Studies (NIES), Japan	AIM
8.5	Integrated Assessment Framework at the International Institute for Applies Systems Analysis (IIASA), Austria	MESSAGE

The RCP scenarios were subsequently combined with 5 SSP scenarios[3] with different socio-economic characteristics (see also Table 2):
– SSP1: Sustainable dev. world (env. tech, good governance, low population, wealthy, social/env goals important)
– SSP2: Medium
– SSP3: Fragmented world (regional competition, low tech., little trade, poor)
– SSP4: Fragmentation in regions (strong rich/poor divide, poor on average)
– SSP5: High economic growth (strong technology, fossil fuel driven, consumption, human development).

Table 2: Main characteristics of the RCP/SSP scenarios (van Vuuren et.al.,2014).

Archetype	Global sustainability	BAU	Regional competition	Economic optimism	Reformed markets	Regional sustainability
SSP mapping	SSP1	SSP2	SSP3/SSP4	SSP5		
Economic development	slow to rapid	medium	slow	very rapid	rapid	medium
Population growth	low	medium	high	low	low	medium
Technology development	medium to rapid	medium	slow	rapid	rapid	slow to rapid
Main objectives	global sustain.	not defined	sucurity	economic growth	various goals	local sustain.
Environmental protection	proactive	both	reactive	reactive	both	proactive
Trade	Globalisation	ɜak globalisati	trade barriers	globalisation	globalisation	trade barriers
Policies and institutions	Strong global governance	mixed	strong national governance	policies create open markets	policies target market failure	local actors
Vulnaribility to climate change	low	medium	mixed	medium-high	low	low
Other mappings:						
SRES	B1(A1T)	B2	A2	A1E		B2
GEO3/GEO4	Sustainability first		Security first	Markets first	Policy first	
Global scenario group	sustainability paradigm		Barbarisation	Conventional world	Policy reform	eco-communalism
Millennium assessment	technogarden		Order from strenghth		Global orchestration	Adapting mosaic

The B2 storyline emphasized a focus on environmental and social issues from a regional perpective. In the quantitative elaboration the choice was made to use medium projections for all relevant variables. Therefore the B2 scenario is listed here in 2 columns

2.1.3 Comparison of available projections

In Figure 3 the TSAP and RCP scenario's are placed in a matrix with one axe (Y-axis) differentiating in Air Quality policies and the other (X-axis) differentiating in Climate Change policies. For TSAP two contrasting scenarios for Air Quality policies are presented (Current legislation and Maximum feasible reduction) but, no differentiation in Climate Change policies has been applied. For the RCP scenario there is a differentiation in as well Climate Change Policies as in Air Quality policies. Looking to the spatial resolution we see that the TSAP scenario's show a relative high spatial resolution (Country level), while the RCP scenario is limited to the EU as a region.

[2] CO2, CH4, N2O, HFC, PFC, SF6, ODS, SO2, BC, OC, NOx, VOC and NH3.
[3] The SSP scenarios can be viewed/download at: https://secure.iiasa.ac.at/web-apps/ene/SspDb

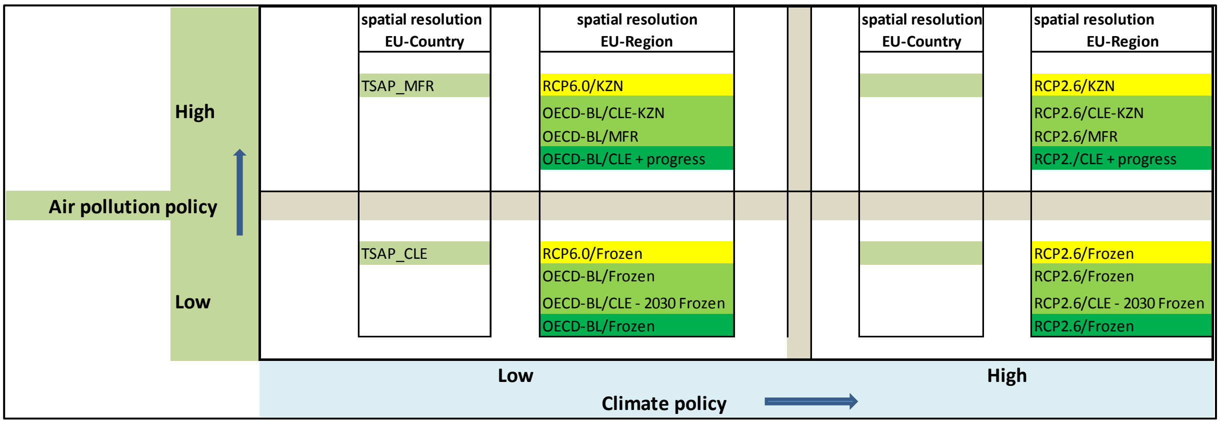

Figure 3: main characteristics in terms of adopted air pollution and climate change control policies

Another challenge to be overcome regards the fact that various scenarios may lack information on the compounds of interest to address air quality and climate interlinkages beyond emissions. For instance, even if RCP include air pollutant emission projections, they were designed primarily for the purpose of large scale chemistry and climate interactions rather than surface air quality assessments, providing insufficient information to allow air quality modelling of air pollutant levels at ground level and their impacts on human health and ecosystems (Colette et al., 2012; Fiore et al., 2012). To overcome the problem of insufficient air pollution information in the RCP scenario's some additional work has been undertaken in new projects such as EC-IMAGE, LIMITS and PEGASOS (Chuwah et. Al, 2013, Braspenning-Radu at al, 2014). In the context of the PEGASOS project, a set of long-term scenarios that are relevant for both climate and air pollution research have been developed (Radu at al, 2012, 2014). They are consistent the RCP scenario's and have additional, detailed, information about air pollutions. Using the derived Emission Factors (EF) for 2030, a set of 10 scenarios was developed by PBL until up to 2100.
For the air pollution policy scenario's the following variants were developed (with 2005 as base year):

1. No improvement of policies after 2005, resulting in frozen emission factors (FRZ).
2. Current policies implemented up to 2030 and constant from 2030 onwards (CLE).
3. Further tightening of CLE after 2030 based on assumptions regarding economic development (CLE KZN).
4. Implementation of maximum feasible reductions until 2030, and constant from 2030 onwards (MFR).
5. MFR with further improvement after 2030 (MFR KZN).

These 5 future air pollution scenarios were combined with 2 sets of climate RCP scenarios (representing 2 radiative forcing targets in 2100: 2.6W/m² and 6W/m²). Table 3 presents the set of emissions delivered to PEGASOS and is available via http://www.eccad.fr

Table 3: Overview of emission datasets produced within the PEGASOS[4] FP7 project.

	PEGASOS
Emission sources	Antropogenic sources
Pollutants	CH4, CO, NOx, NMVOC, SO2, NH3, BC, OC, CO2, N2O
Temporal distribution	Historical part: 1970-2005 Scenarios until 2100
Spatial distribution	Downscaled to 0.5° x 0.5°

2.2 Emission inventories

This section reviews the main issues to be considered when assessing emissions inventories for the present day. As the emissions are an important input variable for modelling/scenario exercises, it's important to take into account :

(1) Comparability of available emission inventories as basis for modelling;
(2) Uncertainties in emission inventories;
(3) Available exercises for gridding of emissions that could be used as input for a more detailed/gridded approach for the metrics.

The main messages from this short analysis, is that the comparability & uncertainties of datasets should be considered when used for downscaling to a higher resolution; especially when we look at (increasingly important) issues like shipping and aviation.

2.2.1 *Consistency across inventories*

In this section the pollutants usually presented in scenario studies and reported in climate change and air pollutant emissions inventories are discussed, including the differences between the (sectoral) split of the pollutants, and their spatial resolution.

EU Member States report their emissions of SO_2, NOx, NMVOCs and NH_3 under the NEC Directive on national emission ceilings for certain atmospheric pollutants (EC, 2001), and emissions of NOx, CO, NMVOCs and SO_2 under the EU Greenhouse Gas Monitoring Mechanism (EC, 2004). This information should also be copied by Member States to the EEA's Eionet Reportnet Central Data Repository (CDR). The three reporting obligations differ in the number and type of air pollutants, the geographical coverage of Parties (for example the inclusion (or not) of overseas dependencies and territories of France, Spain, Portugal and the UK) and the inclusion of domestic and international aviation and navigation in the national total, but for most Parties the differences are only minor. The CLRTAP and NECD reporting formats are identical, CLRTAP and UNFCCC emission inventories differ slightly in the sector split (Table 4).

[4] ftp-ccu.jrc.it/pub/dentener/PEGASOS_WP14/VersionJanuary2014/PEGASOS_DELIVERABLE%2014_1-v1.doc.

Table 4: Main differences between the reporting obligations under the CLRTAP, NECD and the UNFCCC.

	EU NECD	CLRTAP-NFR [a]	EU-MM/UNFCCC -CRF [b]
Air pollutants	NO_x, SO_x, NMVOCs, NH_3	NO_x, SO_x, CO, NMVOCs, NH_3, HMs, POPs, PM	NO_x, SO_x, NMVOCs, CO
Domestic aviation (landing take-off)	Included in national total	Included in national total	Included in national total
Domestic aviation (cruise)	*Not included in national total* [c]	*Not included in national total* [c]	Included in national total
International aviation (landing and take-off)	Included in national total	Included in national total	*Not included in national total* [c]
International aviation (cruise)	*Not included in national total* [c]	*Not included in national total* [c]	*Not included in national total* [c]
National navigation (domestic shipping)	Included in national total	Included in national total	Included in national total
International inland shipping	Included in national total	Included in national total	*Not included in national total* [c]
International maritime	*Not included in national total* [c]	*Not included in national total* [c]	*Not included in national total* [c]
Road transport	Emissions calculated based on fuel sold [d]	Emissions calculated based on fuel sold [d]	Emissions calculated based on fuel sold

***Note**:*

[a] *'NFR' denotes 'nomenclature for reporting', a sectoral classification system developed by UNECE/EMEP for reporting air emissions.*

[b] *'CRF' is the sectoral classification system developed by UNFCCC for reporting of greenhouse gases.*

[c] *Categories not included in national totals should still be reported by Parties as so-called 'memo items'.*

[d] *In addition, Parties may report emission estimates on a fuel consumed basis as a 'memo' item.*

2.2.2 *The specificity of international air and sea traffic*

International Shipping[5]: Emissions from fuels used by vessels of all flags that are engaged in international water-borne navigation. The international navigation may take place at sea, on inland lakes and waterways and in coastal waters. The definition includes emissions from journeys that depart in one country and arrive in a different country and excludes consumption by fishing vessels.

International Aviation: Emissions from flights that depart in one country and arrive in a different country. Include take-offs and landings for these flight stages. Emissions from international military aviation can be included provided that the same definitional distinction is applied.
Emissions from International Shipping have been compared in an assessment published by EEA in 2013 (EEA Technical Report 2013/4, "*The impact of international shipping on European air quality and climate forcing*"), showing that the contribution of international shipping to concentrations of e.g. NO_2 and $PM_{2.5}$ in coastal areas is substantive (e.g varying between 5% and 20% along different European coasts for $PM_{2.5}$). At the same time, the report concludes that there is a strong need for further harmonisation of emissions information from the shipping sector across Europe. The study found that a relative large share of GHG and air pollutants emissions from international shipping is not accounted for in national inventories supporting key conventions.
An unpublished overview (EEA, results of task 1.1.1.9 in 2014 by ETC/ACM) of reported International Aviation data by EU-28 countries compared to Eurostat data, shows large differences between (reported) datasets.
As to allow for further assessment activities, the quality of reported data should be improved – especially in the context of the increasing relative share of international sea traffic and aviation in total emissions

[5] The definitions apply to the present Guidelines and are taken from chapters 3.5.1 and 3.6.1 of volume 2 of the IPCC Guidelines (IPCC, 2006).

2.2.3 *Spatial resolution and geographical target areas.*

Especially for air pollution impact studies the spatial resolution and characteristics (height, variation over the year, temperature) of the emitted pollutant is important in order to calculate the exposure/concentration. In most (global) assessment of climate change models/scenario studies, the spatial resolution is usually at the national/regional scale. A number of methods exists to downscale these emissions to a higher spatial resolution. In the next paragraphs a few of these methods are discussed and assessed on their suitability for high quality, European, impact studies

2.2.3.1 Downscaling based on high resolution social economic data

Downscaling emissions to (sub) national level can be performed on the basis of population, economic data (van Vuuren et al., 2007). Emissions are dependent on population and per capita income levels, but also on technological advances such as energy efficiency and the type of fuels used. This interdependence has been described by several simplified equations, such as the IPAT equation (Ehrlich and Holdren, 1971) and the related Kaya identity (Kaya, 1989). The IPAT equation represents environmental impact (I) as the product of three indicators: population (P), affluence (A) and technology (T). Using emissions for impact, per capita income levels for affluence and emission intensity (emissions per unit of GDP) for technology yields an identity equation that can be used to analyse trends in emissions. For all energy and industry related emissions (the majority of emissions), a possibility could be to apply the IPAT equation (used so far exclusively to model the temporal evolution) to downscale spatially the emissions by population growth and income level increase. Since the other categories are only loosely linked to consumption (and much more to production) simple linear downscaling is used for these categories.

Emission intensity generally decreases over time in most scenarios. As with per capita income levels, most scenarios—including IPCC-SRES—show partial convergence of emission intensities across regions over time. This convergence is driven by a spread of technologies, but also by maturing economies (i.e. post-agricultural advancing to post-industrial economies) all around the world. As emission intensities converge at the regional level, it makes sense, once again, to use a convergence algorithm for downscaling regional emission intensities).

2.2.3.2 The EMEP gridding process

EMEP, under the convention for long range air pollution, has a long experience with the downscaling of reported data in order to run their EMEP model. Depending on the provided data they have different methods, Figure 4 shows the general approach.

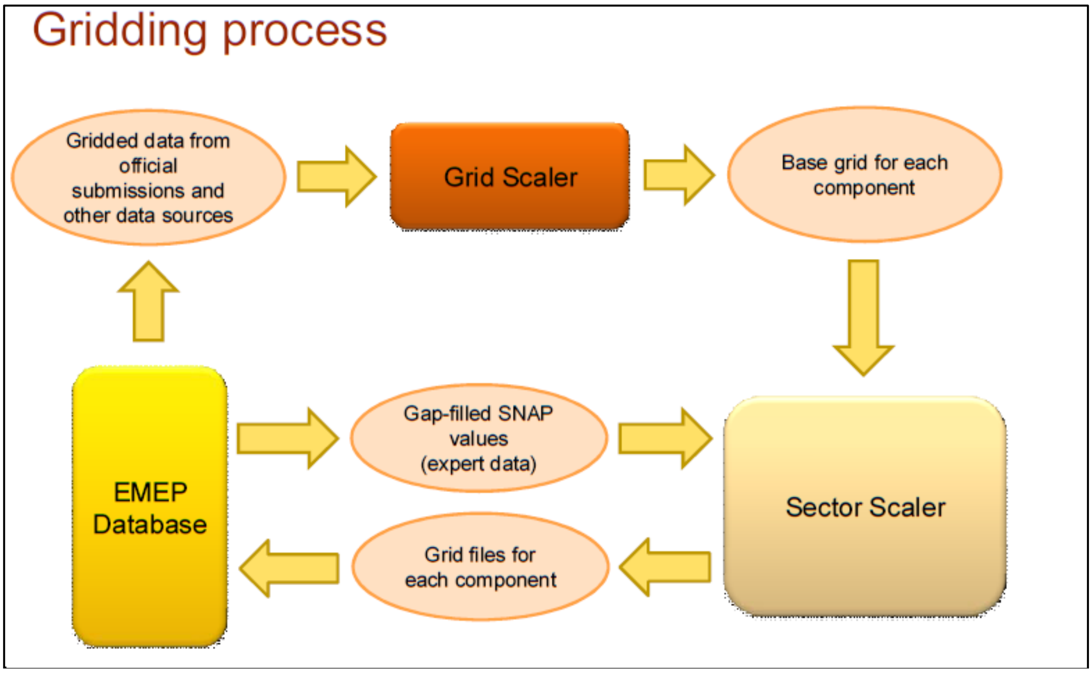

Figure 4: general approach of the EMEP methodology for downscaling of data.

2.2.3.3 Edgar database

JRC maintains a global, gridded database with the most important AQ and GHG emissions (See: http://edgar.jrc.ec.europa.eu/overview.php?v=42). The database is regularly updated on the basis of scientific insights. Edgar can be of help as an independent dataset for those regions where there is a lack of officially reported data; but also as a check for data reported by countries. Furthermore, the fact that Edgar is regularly updated is a big advantage compared to projects where emissions are gridded as a one-off activity.
The availability of Edgar data allows for a modelling exercise at a more detailed level, combining global scenario's with downscaled calculated emissions that can be applied in atmospheric dispersion modelling. In that sense, Edgar may help in downscaling AP/ GHG metrics to a regional / country level.

2.2.3.4 TNO/MACC and INERIS/EC4MACS approaches

There are several possibilities to downscale emissions up to a resolution of about 7km from the emission totals provided at country-scale or on coarse geographical grids (e.g. the 50km resolution of EMEP emissions) using external proxies. TNO and INERIS (Figure 5) are both developing such approaches. Both use high-resolution population density maps to re-distribute residential emission and road network maps for the traffic sector. Using the large point source location and fluxes provided in E-PRTR is also standard practice.

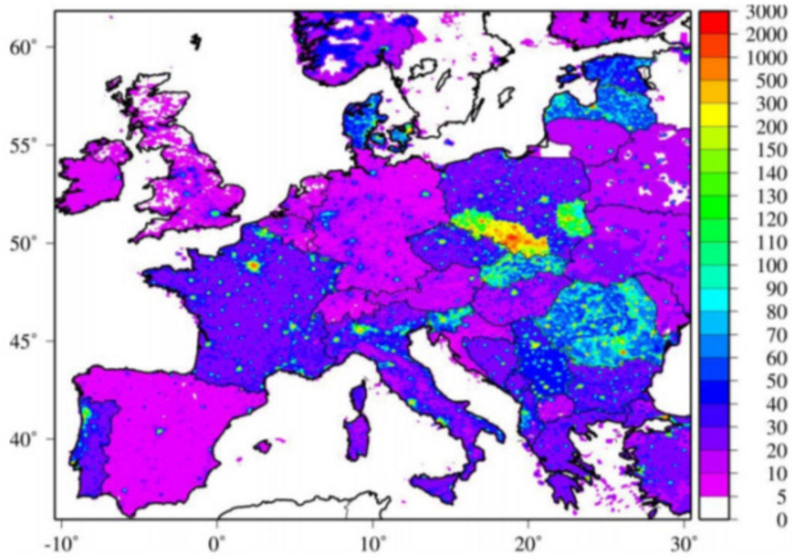

Figure 5: Total annual primary particle emission with diameter below 2.5 µm attributed to the residential sector (g/km^2) (Terrenoire et al., 2013).

2.2.3.5 IER (Univ. Stuttgart)

In 2010/2011, the University of Stuttgart (Theloke et al) developed a European overview of gridded emissions on the basis of emissions reported by the EU countries under E-PRTR provisions. The results were presented e.g. during the meeting of the Task Force Emission Inventories and Projections (TFEIP) in 2011 (http://tfeip-secretariat.org/2011-tfeip-meeting-sweden/).

As discussed during this task force meeting, the proxies applied in this study for Europe are the same for all countries. That is, on one hand, an advantage, because it increases comparability and consistency in the gridded dataset . On the other hand, specific circumstances per country are not taken into account. For assessing the related uncertainties, Theloke compared his Europe-covering approach with the gridded emissions for the Netherlands; and more specifically NOx from residential combustion. The results of this exercise are shown in Figure 6.

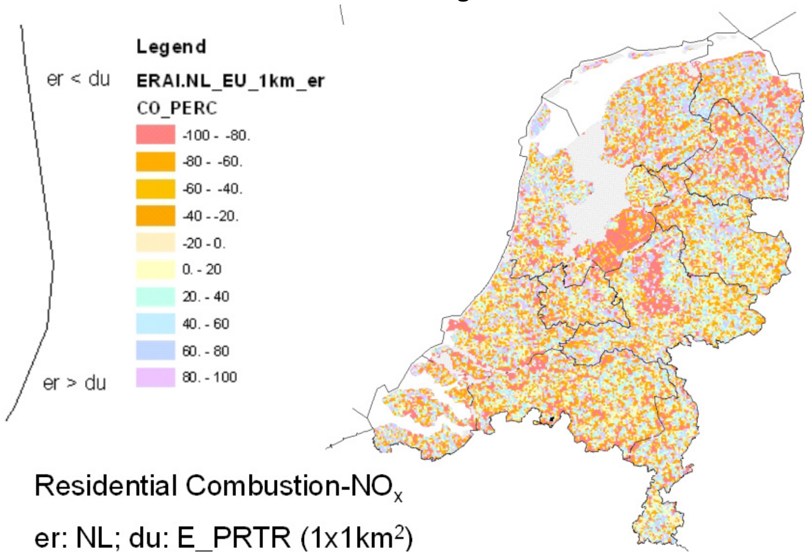

Figure 6: relative differences (in %, NL PRTR compared to IER study) between NOx emissions attributed to Residential combustion according to a national gridding and a European approach due to differences in proxies as applied for gridding the same overall national total emissions for this sector.

2.3 Summary and ways forward

2.3.1 Air and Climate emission projections

To get more information about the current status of the research in the area of integrating Air Quality and Climate Change and on possible ways forward, an interview was conducted with a number of experts in the field. The results of the interviews are synthesized here:

1. It should be noted that in recent years scenario studies the number of scenarios addressing both fields has increased and both the Air Quality community (TSAP) and the Climate Change community (RCP) have conducted an in-depth scenario for the medium to long-term horizon.
2. Global emission inventories and - in turn - scenarios often have a limited spatial representation of the EU (a few regions). European assessments requires a spatial resolution of national scale and in some cases down to gridded/agglomerations. **Proposed is that EEA will further develop methods to downscale emission data for instance by following the examples of the developments conducted by TNO (MACC) or INERIS (EC4MACS) in producing high-resolution pan European inventories. There are also ongoing activities in a number of EEA member states (e.g. France, UK, Netherlands, Spain,...) to develop high-resolutions (~1km) bottom-up inventories. There is scope to make use of such high-resolution inventories as proxies to produce high-quality inventories consistent with officially reported emissions at the country level, as initiated by INERIS for the EuroDelta exercise in support of the CLRTAP/TFMM[6].**
3. Most existing projections are focused on regulatory and/or technological alternatives. Air pollution is often focused on EOP, being the economic costs with lowest uncertainty; it is more straightforward than an integrated approach including structural changes and taxation of remaining emission damage on the environment. **It is important to include more structural/behavioural options in scenarios** (i.e. reduced meat consumption, efficient use of heating in houses, taxing damage to the environment, ...) . It is proposed that EEA takes the initiative to explore this approach.
4. Scenarios are often developed with a climate change policy first and then some additional AQ policies are added. **It is proposed that EEA would develop a scenario the other way around, i.e. first define stringent AQ policy till 2050, calculate the co-benefits for CC and derive the remaining policies required to reeds the T-CC target.**

2.3.2 Comparing reported emission data

The reported data to the various bodies responsible to collect emission data and used in dispersion models can differ substantially. Therefore scenario studies can differ in outcome, even if they include the same measures. The base year for the calculation and the source used is therefore important. Figure 7 shows national emissions, for the same base-year, for three different, well-known sources. As can be seen easily there are remarkable differences. Climate change and air quality communities use often different datasets for their base year data, it is therefore important to note this and if possible find methodologies to deal with these differences. As a minimum, transparency is needed on base year, which measures are included and how they are taken into account in the scenario analysis. As found by ETC/ACM 2011 (ETC/ACM Technical paper 2011/20 Cobenefits of Climate and Air Pollution Regulations), this is not always reported transparently. In some cases, **using relative changes instead of absolute changes can be a solution instead of emission total for the present day are more robust across inventories.**

[6] https://wiki.met.no/emep/emep-experts/tfmmtrendeurodelta

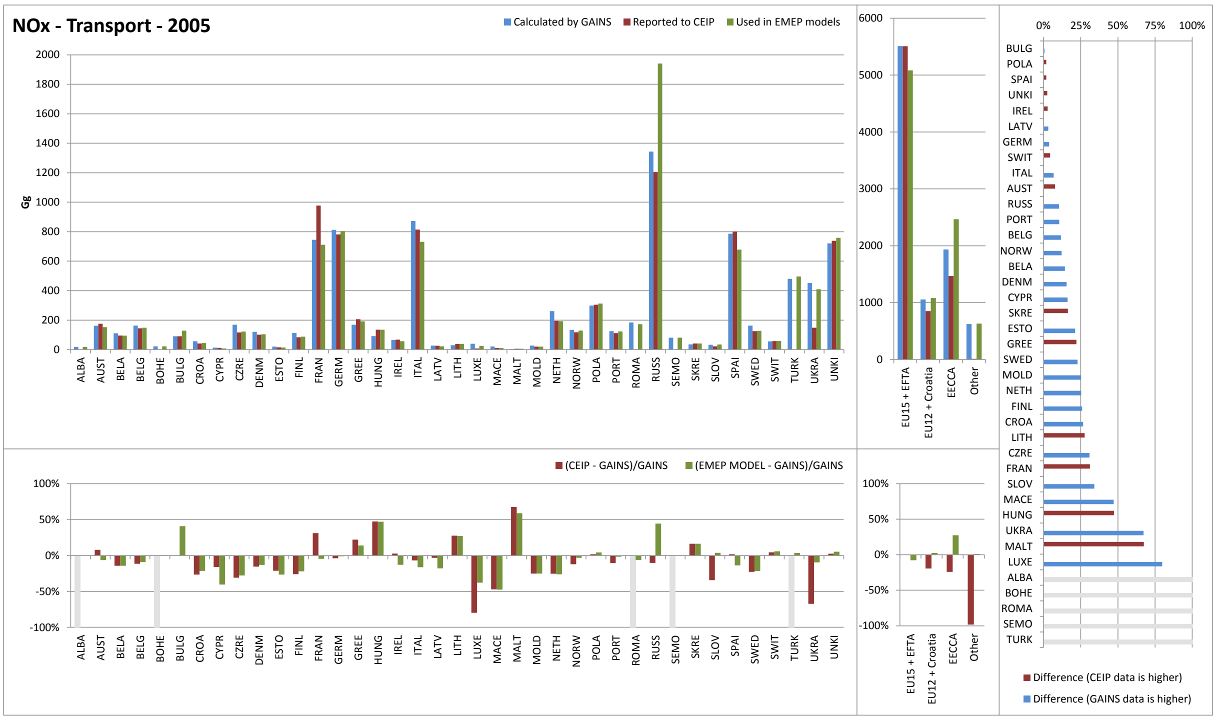

Figure 7 Overview of differences in reported emissions for three different purposes (Emissions as reported by countries under LRTAP (CEIP), EMEP model and GAINS approach),
(source: http://www.ceip.at/fileadmin/inhalte/emep/pdf/gridding_process.pdf).

2.3.3 Spatialisation of emissions

Substantial progress has been achieved in improving the spatial distribution of emission inventories, especially over Europe. The topic remains however in development as part of research projects whose limited duration raise a concern of continuity given that such endeavour require periodical updates.

Further development of high-quality proxies for downscaling using a top-down approach is still needed until high-resolution bottom-up inventories such as those available in France and UK and developed in the Netherlands are generalized across the continent. **Agriculture is amongst the activity sectors where such proxies are still highly uncertain.** Top-down approaches offer the benefit of relying on consistent proxies across a wide geographic area. However for the sake of completeness, such proxies are often superficial so that **bottom-up inventories are generally considered higher in quality**. In addition these downscaling gridding exercises do not take into account changes in economic structure over time; so that they are linked to the current (economic) circumstances. Whereas a change in economic structure over time in a country may of course also lead to a change in the distribution of emissions in a country.

3 Climate impacts

3.1 Introduction

Emissions of greenhouse gasses and air pollutants lead to changes in atmospheric composition and often subsequently climate forcing and changes, and its impacts and responses (known as the DPSIR chain, = Drivers, Pressures, State, Impacts and Response, Figure 8). The climate forcers and air pollutants should not be considered in isolation as they interact at multiple ways. Studies have, for example, shown that reducing emissions from short-living compounds including some air pollutants could be very effective (=in limiting temperature rise) to “buy time” to deal with CO_2 and other long-term gasses (Tol, et al, 2012; Solomon et al, 20132013), something that is important from the perspective of preparing the environment and society (=adaptation). Likewise air pollutants can have an effect on the precipitation patterns by affecting the number and size of clouds (Koren et al, 2014) and reforestation (often seen as a climate change mitigation measure) can be a cost-effective abatement measure for ground-level ozone and nitrogen oxide (Kroeger et al, 2014).

In order to quantify and communicate the contributions to climate change of emissions of different compounds, and of emissions from different regions/countries or sources/sectors, metrics are needed. Some metrics are designed with specific (policy) goals in mind, such as the compliance with air quality standards (e.g., $PM_{2.5}$ concentrations), others by contrast have been adopted in policy discussions without the original intention for policy use (Schmale et al, 2014). Note that no single metric can accurately compare all consequences of different emissions in the different stages of the DPSIR chain, and all have limitations and uncertainties (Peters et al, 2011). Furthermore, metric values are also strongly dependent on which processes are included in the definition of a metric, and on input parameters and assumptions used. Regarding the latter, uncertainties increase with longer considered time horizon (Reisinger et al., 2010; Joos et al., 2013) and metrics that account for regional variations in sensitivity to emissions or regional variation in response could give a different emphasis to emissions of specific pollutants.

Using different metrics can result in different estimates of required emission reductions in the short and long-term (Brennan and Zaitchik, 2013). One important issue here is that an equal-mass emissions from different regions can vary in their global-mean climate response, an issue that is especially relevant for less homogeneous distributed/short-lived climate-forcing pollutants (SLCPs) such as black carbon and methane. Reducing emissions of SLCPs can provide immediate (local) benefits for health and agriculture and can considerably mitigate climate change (Worldbank, 2013). Note that without mitigation of CO_2, reductions in SLCPs can only delay, but not prevent, a substantially greater warming in the longer term (UNEP, 2011). To effectively integrate air pollution and climate change objectives into SLCP reduction strategies, technical metrics need to be used that capture the benefits and trade-offs from both arenas while avoiding inappropriate substitution between SLCP and CO_2 mitigation.

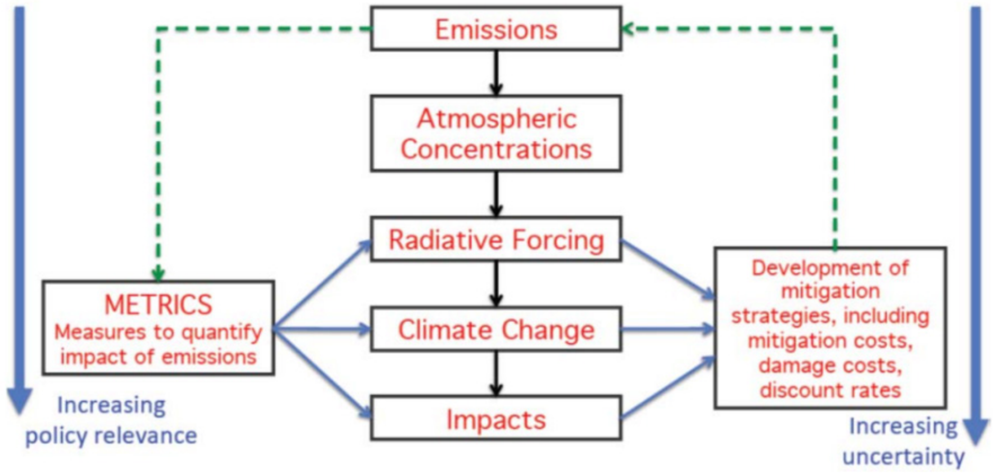

Figure 8: *The DPSIR chain from emissions to climate change and impacts showing how metrics can be defined to estimate responses to emissions (left side) (and for development of multi-component mitigation, right side). The relevance of the various effects increases downwards but at the same time the uncertainty also increases (IPCC, 2013, figure 8.27)*

One of the objectives of this chapter is to present an overview of possible metrics that combine climate forcers and air pollutants. Furthermore, we provide some backgrounds behind these metrics (e.g. on spatial resolution) and how these are included in different models and scenarios (both in section 3.2). Finally, based on the comparison of metrics and the assessment of models and scenarios, the chapter also summarizes some recommendations for future research. In this chapter we focus on the interactions in the atmosphere ("state"). Air pollutants and climate forcers also interact when affecting ecosystems and human health ("impacts").
Note that we focus here on the direct interlinkages between climate forces and air pollutants with respect to emissions of individual gasses and their concentration. As such, we neglect here indirect interlinkages. For example, acidification, nitrogen deposition and ozone may lead to ecosystem degradation, affecting land-cover characteristics, albedo and thus the climate system (e.g. Sitch et al, 2007).

3.2 Synthetic overview of metrics availability

The total contribution of air pollutants and climate forcers can be quantified and communicated in multiple ways/using different metrics. Here we assess these metrics, and provide information on the advantages and disadvantages. We distinguish between metrics that are based on (changes in) atmospheric **composition** or **emissions**. A detailed overview on the methodology and analytical formulation of these metrics can be found in (Aamaas et al., 2013). Furthermore, we evaluate how they have been included in existing European and global scenarios.

3.2.1 *Concentration metrics*

Radiative Forcing (RF) and more recent Effective Radiative Forcing (ERF) are two metrics that are used to quantify the change in the Earth's energy/radiation balance - as measured at the top of the atmosphere - that occurs as a result of an externally imposed change like changing atmospheric composition (see IPCC, 2013 for details). The atmospheric forcing is, for example, relevant when assessing the likelihood of limiting long-term global temperature increase up to 2K (=the most relevant policy target in climate change, Van Vuuren et al, 2014, Figure 9).

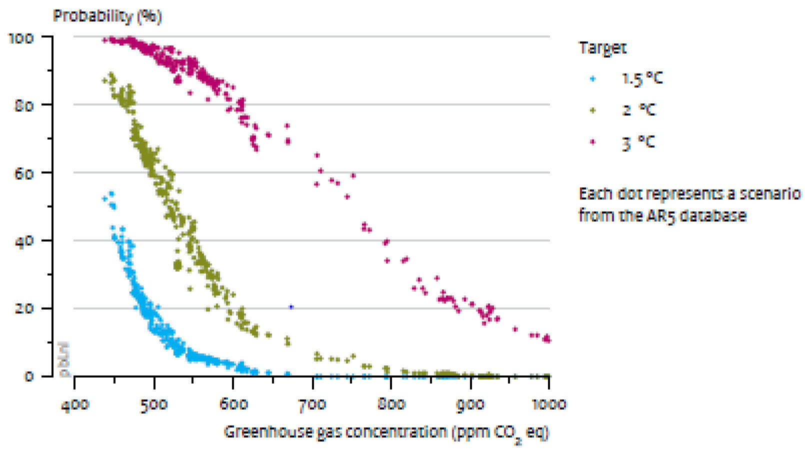

Figure 9: Probability of achieving temperature targets as a function of greenhouse gas concentration levels (Source Van Vuuren et al, 2014).

RF and ERF are both expressed in watts per square metre (W m^{-2}), often used to assess the total forcing over the industrial era from 1750 to present (/2011), but also applied in multiple scenario analysis to assess the future forcing (e.g. Thomson et al, 2011 and Shindell et al, 2013). The RF and ERF values are compounds specific. Positive values indicate more incoming radiation and as such a warming of the atmosphere, negative values depict a surface cooling.

There is a need to distinguish between direct/instantaneous and indirect forcing when assessing the effect on the global and regional radiation balance (IPCC, 2013). Direct RF and ERF refer to the change of fraction of light being absorbed (warming) by well-mixed greenhouse gases, tropospheric ozone, stratospheric water vapour or scattering (cooling) by stratospheric ozone and aerosols. Indirect RF and ERF refer to aerosols altering cloud properties resulting in the inference of incoming solar radiation with clouds (cooling) or the formation of contrails or contrail induced clouds by aircraft (warming). E.g. Rosenfeld et al (2014) indicated that only little additional aerosols are need to change cloud characteristics and thus climate change. Other indirect effects are deposition of black carbon on ice and snow resulting in less solar radiation being reflected by these surfaces (warming) with as consequence a faster melting of snow and ice masses (EEA, 2012)

The RF concept has been used for many years and assessments – like IPCC assessment reports - for evaluating and comparing the strength of the various compounds in the atmosphere and mechanisms affecting Earth's radiation balance and thus causing climate change. The total values of well-mixed GHG has increased about 7% between 2005 and 2011 (Table 5). But the relative contributions of these WMGH Gases were relatively stable; changes were due to increasing emissions. This is somewhat different for most aerosols (Table 6). In the IPCC 4th Assessment a best estimate of their RF of –0.5 ± 0.4 W m^{-2} was given for the change in the net aerosol–radiation interaction between 1750 and 2005 (IPCC, 2007). In the more recent assessment this estimate has been lowered down to –0.35 ± 0.5 W m^{-2} (IPCC, 2013). It is noteworthy to emphasise that the range of uncertainty has increased between the fourth and fifth Assessment Reports, and a recent study reported that this uncertainty range was still substantially underestimated (Samset et al., 2014), highlighting the need to (1) be cautious about policy conclusions that can be drawn on the climate impact of aerosols, and (2) support ongoing research on the topic. In quantitative terms we see now a strong cooling effect of sulphate aerosols and an increased strong warming due to black carbon (Table 6, Figure 10).

From the perspective of synergies between air and climate change, Figure 10 can be summarized in three blocks. First, the well-mixed gasses, consisting of the compounds of the Kyoto plus Montreal Protocol (with an overall historic forcing of about 2.8 W/m^2 up to 2011), where the synergy with air pollution is limited. This is more the case for the second and third block. The second block consists of aerosols, which have in general a cooling effect (historically -0.35 W/m^2), with the exception of black carbon). The third block is the group of ozone precursors, consisting of CO, VOCs, NOx and CH_4. Increased concentrations result in general in more tropospheric ozone and as such –indirectly- in more warming (historically 0.42 W/m^2). So, when abatement strategies to limit air pollution in Europe become implemented, the net effect on the climate system depends very much on the type of measure and related compound.

Table 5: Climate forcing for 2011 and 2005 for the Well-mixed GHGes, based on NOASS and AGAGE data (source IPCC, 2013)

Species	Radiative forcing (W.m^{-2})	
	2011	2005
CO_2	1.82	1.66
CH_4	0.48	0.47
N_2O	0.17	0.16
HFC & SF6	0.03	0.02
Montréal Gasses	0.33	0.33
Total	**2.83**	**2.64**

Table 6: Global and annual mean RF (W m^{-2}) due to aerosol–radiation interaction between 1750 and 2011 of seven aerosol components for AR5. Values and uncertainties from SAR, TAR, AR4 and AR5 are provided when available.

	Global Mean Radiative Forcing (W m^{-2})			
	SAR	TAR	AR4	AR5
Sulphate aerosol	–0.40 (–0.80 to –0.20)	–0.40 (–0.80 to –0.20)	–0.40 (–0.60 to –0.20)	–0.40 (–0.60 to –0.20)
Black carbon aerosol from fossil fuel and biofuel	+0.10 (+0.03 to +0.30)	+0.20 (+0.10 to +0.40)	+0.20 (+0.05 to +0.35)	+0.40 (+0.05 to +0.80)
Primary organic aerosol from fossil fuel and biofuel	Not estimated	–0.10 (–0.30 to –0.03)	–0.05 (0.00 to –0.10)	–0.09 (–0.16 to –0.03)
Biomass burning	–0.20 (–0.60 to –0.07)	–0.20 (–0.60 to –0.07)	+0.03(–0.09 to +0.15)	–0.0 (–0.20 to +0.20)
Secondary organic aerosol	Not estimated	Not estimated	Not estimated	–0.03 (–0.27 to +0.20)
Nitrate	Not estimated	Not estimated	–0.10 (–0.20 to 0.00)	–0.11 (–0.30 to –0.03)
Dust	Not estimated	–0.60 to +0.40	–0.10 (–0.30 to +0.10)	–0.10 (–0.30 to +0.10)
Total	Not estimated	Not estimated	–0.50 (–0.90 to –0.10)	–0.35 (–0.85 to +0.15)

Whereas in the RF concept all surface (e.g. albedo) and tropospheric concentrations are assumed to remain constant, the ERF calculations allow most physical variables (except for those concerning the ocean and sea ice) to respond to perturbations like changes in clouds and on snow cover (these changes occur on a time scale much faster than responses of the ocean - even the upper layer - to forcing)[7]. Hence ERF includes both the effects of the forcing agent itself and the rapid adjustments to that agent (see Shindell et al, 2013 for more details on ERF). ERF is thus seen now as a more applicable metric to quantify the forcing of those components that respond rapidly to changes in the atmosphere and surface characteristics – like aerosols (IPCC 2013, Figure 10). And even for CO_2 the ERF could be different from the RF, because CO_2 can also affect climate through physical effects on lapse rates and clouds. However, due to contrary effects it is therefore not possible to conclude whether the ERF for CO_2 is higher or lower than the RF. Therefore IPCC had defined a ratio ERF/RF to be 1.0 with an uncertainty in the CO_2 ERF to be –20% to 20% (IPCC, 2013). Further note that the calculation of ERF requires longer simulations with more complex models than calculation of RF (IPCC, 2013).

[7] See http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-8-5.html for the way how ERF is defined

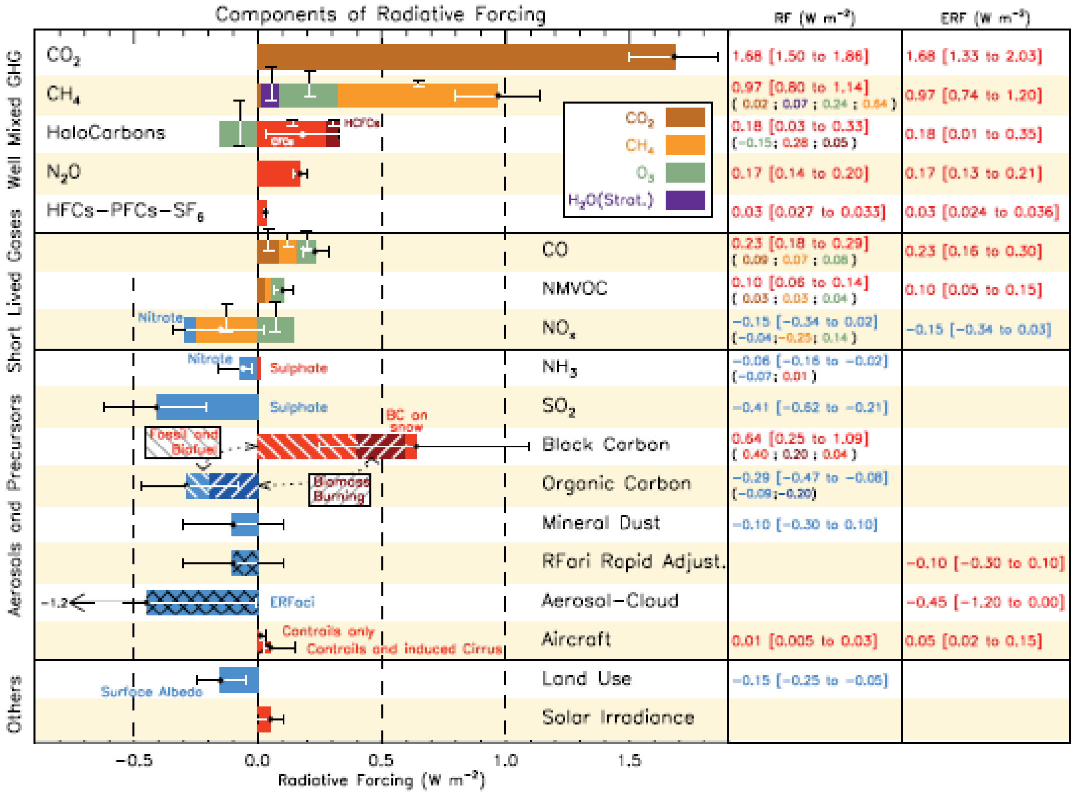

Figure 10: Radiative forcing (RF) of climate change during the industrial era shown by emitted components from 1750 to 2011. The horizontal bars indicate the overall uncertainty, while the vertical bars are for the individual components (vertical bar lengths proportional to the relative uncertainty, with a total length equal to the bar width for a ±50% uncertainty). The coloured box refers to direct or indirect way of how contribute to the forcing. See text for some assessment of the numbers (Source IPCC, 2013).

By nature, well-mixed GHGs such as CO_2 are quite homogenous distributed across the world, and forcing per unit emission and emission metrics for these gases thus do not depend on the geographic location of the emission. These gasses have the largest forcing in warm and dry regions (esp. the subtropics), decreasing toward the poles (Taylor et al., 2011). For the short-living climate forcers (SLCFs) the time scale over which their impact on climate is felt is short. Nevertheless their forcing might be relevant, for example to define the need to rapid adaptation ("buying time"). Their concentration spatial pattern and therefore their RF pattern are highly inhomogeneous, and meteorological factors such as temperature, humidity, clouds, and surface albedo largely affect how concentration translates to the forcing.

3.2.2 Emission metrics

Multiple metrics can be defined to quantify, compare, and communicate the relative and absolute contributions to climate change of emissions of different substances, of emissions from regions/countries or of sources/sectors, and as such to show the co-benefits of policies and measures. Note that no single metric can yet compare all consequences (i.e. responses in climate parameters over time) of different emissions. The choice of metrics depends strongly on (i) the particular consequence one wants to evaluate; and (ii) how comprehensive a metric needs to be in terms of indirect effects, feedbacks and economic dimensions (Peters et al, 2011; IPCC, 2013).

The Global Warming Potential (GWP) and Global Temperature Change Potential (GTP) are two frequently used concepts (See Fuglestvedt et al. (2010) and IPCC (2013) for a detailed description).

GWP integrates the total radiative forcing of a pollutant over a chosen time horizon due to its emission, relative to that of CO_2 (without dimension). As such GWP could be seen as an index for the total energy added to the climate system by a pollutant relative to that added by CO_2 (IPCC, 2013).

When it comes to assessing the warming potential of non-CO2 traces species, the long lifetime of CO2 also plays a role. Since the GWP of any species is normalized by that of CO2, after a few years the signal becomes dominated by the CO2 warming potential. This feature is illustrated in Figure 11 that shows the absolute GWP of methane, black carbon and CO2 in the coming centuries. The AGWP of CO2 is the same in both plots. Because of their shorter lifetimes, the pulse of CH4 and BC vanishes after a few decades (CH4) or years (BC). Therefore their AGWP (defined as an integral forcing up to a given time) becomes constant. On the contrary, the AGWP of CO2 keeps increasing, so that the GWP of CH4 and BC is eventually constrained by the CO2 response alone.

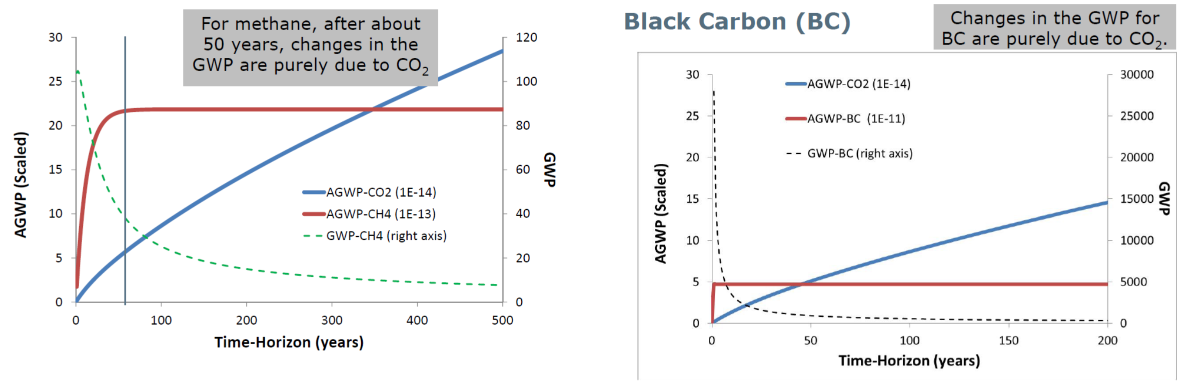

Figure 11: Absolute and Relative global warming potential (AGWP and GWP) of methane (left) and black carbon (right) compared to the AGWP of CO2, (Fuglestvedt et al., 2012).

In order to avoid this 'artifact', the Global Temperature Potential (GTP) was designed as an alternative metric. The GTP is defined as the ratio of change in global mean surface temperature (GMST) at a chosen point in time from the substance of interest relative to that from CO_2 (as such without dimension). GTP relies on the temperature perturbation (instead of the radiative forcing) at a given time horizon (instead of cumulated up to a given time horizon). By including the climate response in its design, the GTP copes for the shorter lifetime of near term climate forcers by taking into account the longer term impact of the perturbation transferred to the climate compared to the lifetime of the compound itself.
The behaviour of GTP is quite similar as GWP for long lived species. Like GWP, the GTP values can be used for weighting the emissions of greenhouse gasses and pollutants to obtain "CO_2 equivalents". This gives the temperature effects of emissions relative to that of CO_2 for a chosen time horizon. For an analogous to GWP that integrates temperature effect up to a given horizon, one can refer to the integrated GTP (iGTP), (Olivié and Peters, 2013).Both for GWP and GTP the choice of the time horizon has a strong effect on the relative importance of near-term climate forcers and well-mixed GHGs to the total forcing. When, for example, using a very short time horizon, short-term climate forcers, such as black carbon, sulphur dioxide or CH_4, can have contributions comparable to that of CO_2 (of either the same or opposite sign), but their impacts become progressively less for longer time horizons over which emissions of CO_2 dominate (IPCC, 2013).

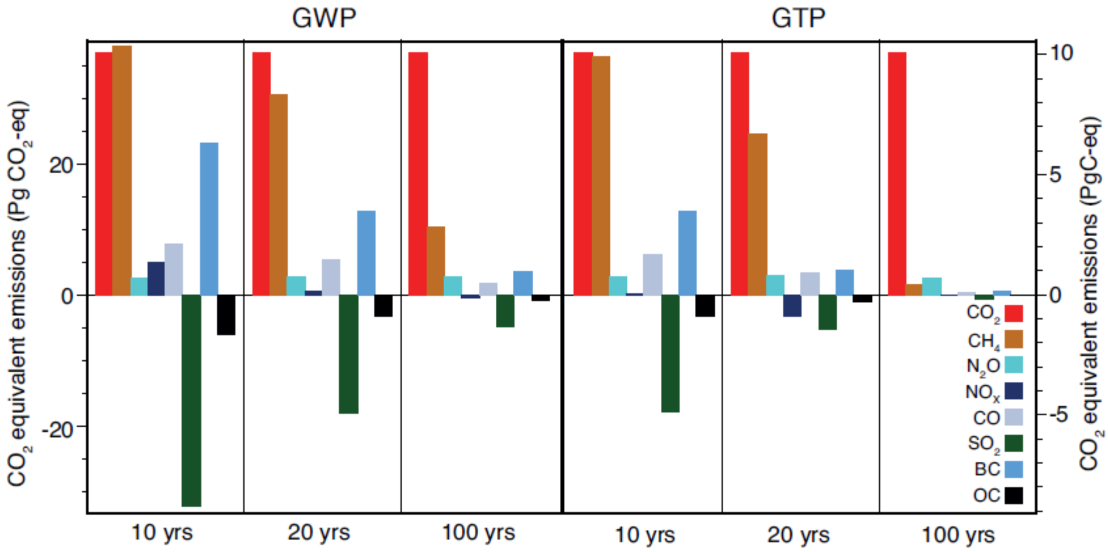

Figure 12: Global anthropogenic present-day emissions in terms of Global Warming Potential (GWP) and the Global Temperature change Potential (GTP) for selected time horizons. Units are 'CO_2 equivalents', which reflects equivalence only in the impact parameter of the chosen metric, given as Pg(CO2)eq (left axis) and PgCeq (right axis). Source: IPCC, 2013

In contrary to GWP, GTP is for the moment only used in the physical science framework (Fuglestvedt et al., 2010; Shine et al., 2007), although its advocate make the case for its use in the policy arena to address SLCPs. The fundamental different characteristics of GTP compared to GWP are:

- GWP is a metric that integrates over time, i.e. puts equal weight on all times between the emission and the time horizon. GTP, in contrary, is an "end-point'' metric, i.e. the temperature change at a particular time in the future (e.g. plus 2^{o}C).
- GTP takes into account the transfer of energy of the radiative forcers to the climate system. While the GWP of a species is zero once it has exceeded its lifetime (i.e. has been removed from the climate system), the GTP takes into account the fact that the species has transferred energy to the system, and that inertia shall be added to the lifetime of the radiative compound itself. This feature is of course specifically relevant for SLCPs that have, by nature, a shorter lifetime because of their physical (e.g. wet deposition) or chemical (oxidation) removal from the atmosphere.
- GTP is further down the cause and effect chain from emissions to impacts (DPSIR), causing also greater uncertainty (Figure 8). For example, GTP requires additional information such as climate sensitivity.
- Despite that there are significant uncertainties related to both GWP and GTP, the uncertainties of GTP are larger than those of GWP. For the 100-year absolute GWP of CO_2 the uncertainty can be as large as ±26%, for CH_4 even ±40% (Reisinger et al, 2011; Boucher, 2012). The fact that GTP has been introduced more recently and addressed in relatively less studies than GWP also contribute to this higher uncertainties.

The use of GWP and GTP has advantages and disadvantages. An advantage is that both are suited to address the climate impacts of past or current emissions attributable to various activities. From this perspective, the energy and industry sector has the largest contributions to warming over the next 50 to 100 years, while animal husbandry, waste/landfills and agriculture are relatively large contributors to warming over time horizons up to about 20 years (due to the large emissions of CH_4 (IPCC, 2013).

Limitations deal, for example, with:

- inconsistencies related to the treatment of indirect effects and feedbacks, for instance, if climate–carbon feedbacks are included for the reference gas CO_2 but not for the non-CO_2 gases;
- The uncertainties related to both GWP and GTP increase with time horizon, complicating the application for assessing long-term strategies (e.g. 20-year absolute GWP of CO_2 is about 18%, for 100-year GWP, 26%);
- The choice of metric and time horizon is related to a particular application (implicit value-related judgements) and which aspects of climate change are considered relevant in a given context. At the same time, the values are very dependent on chosen time horizon;
- Metrics do not define policies or goals but facilitate evaluation and implementation of multi-component policies to meet particular goals.

Given these uncertainties and limitations, the type of metric chosen and selected time horizon may have for many components a much larger effect than improved estimates of input parameters (IPCC, 2013). This is important when assessing perceived impacts of emissions and abatement strategies. For example, Wang et al (2013) have shown that when the country's GHG emissions are calculated with GTP instead of GWP, the shares of, for example, the EU and USA rise in the period 1990-2005, and those of some other countries like Australia, China and India decrease. According to these authors, the reason for this may be found in the structure of GHG emissions, particular in the share in which methane emissions contribute to the total emissions of a country. More research would be needed to clarify this.

Another example of the importance of uncertainties in climate metrics is presented in Figure 13. This shows the GWP of TSAP scenarios split by air pollutant when using either default or upper/lower estimates of GWP20. Using default values, it is found that the overall effect of these SLCPs is small, but negative (=cooling) for the period 2010 to 2025. When, however, using the given upper values the overall effect of the air pollutants becomes positive (warming). Especially the wide range in GWP values for BC caused this change. This shows the significance of the uncertainty of these pollutants to the future climate and in particular the uncertainty around black carbon is very large.

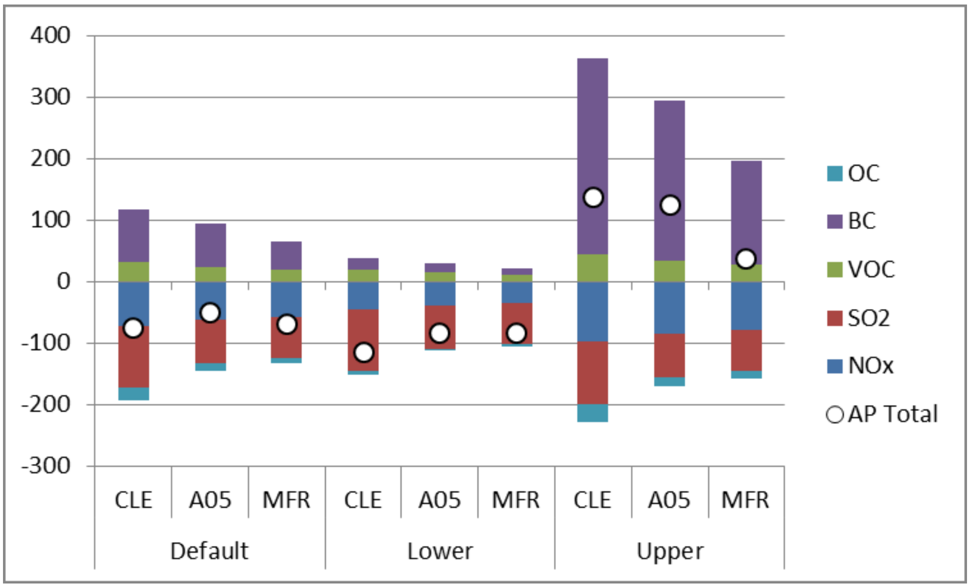

Figure 13: Uncertainty of EU28 emissions in the TSAP 2013 scenarios expressed as GWP20 for each compound, and net effect (white dots)

More recent new metrics have been or are being developed, partly based on the original GWP and GTP concepts (IPCC, 2013) (see Table 7 and Table 8). This to (i) tackle some of the shortcomings of these approaches and (ii) to include more economics dimensions. Examples are:

- GWP_{bio} and GTP_{bio} to assess the effectiveness of biomass combustion for energy, i.e. include the time lag between combustion/use of biomass and regrowth/CO_2 uptake of plants. During this period CO_2 is resident in the atmosphere and leads to an additional warming (Cherubini et al., 2011);
- Absolute Regional Temperature Potential (ARTP) is an metrics for better capturing the sub-global/regional patterns of responses (Tol et al., 2012; Shindell, 2012; Collins et al., 2013). ARTP gives the time-dependent temperature response in four latitude bands as a function of the regional forcing imposed in all bands;
- Component-by-component or multi-basket approach (e.g. Smith et al., 2012). In this approach multiple gases are divided into two baskets (gases with long lifetimes and short-lived gases, incl. CH_4). The two baskets are then presented two metrics that can be used for estimating peak temperature for various emission scenarios.
- Global Cost Potential (GCP) which is the estimated costs for emission reduction that are needed to attain certain climate target (Toll et al, 2012, UNFCCC, 2012; Ekholm et al, 2013);
- Climate Change Impact Potential (Kirschbaum et al, 2014). This new is based on explicitly defining the climate change perturbations that lead to three different kinds of climate change impacts (1) those related directly to temperature increases; (2) those related to the rate of warming; and (3) those related to cumulative warming.

Overall these new metrics have been applied only in few studies. And for the Climate Change Impact Potential, values are only available for the greenhouse gasses (Kirschbaum et al, 2014). As such more research and applications are needed to assess the usefulness and robustness of results (Shindell et al., 2012, IPCC, 2013).

Table 7: GWP and GTP values (without dimension) for greenhouse gasses for a time horizon of 20 and 100 years (based on IPCC, 2013; Joos et al., 2013). Note that numbers do not include climate feedbacks (see IPCC, 2013 for discussion on this).

		GHG	GWP		GTP	
			20	100	20	100
		CO2	1	1	1	1
		CH4	84	28	67	4.3
		N20	264	265	277	234
F gasses Kyoto	HFCs	HFC-23	10800	12400	11500	12700
		HFC-32	2430	677	1360	94
		HFC-41	427	116	177	16
		HFC-43-1(	4310	1650	3720	281
		HFC-125	6090	3170	5800	967
		HFC-134	3580	1120	2660	160
		HFC-134a	3710	1300	3050	201
		HFC-143a	6940	4800	6960	2500
		HFC-152a	506	138	174	19
		HFC-227E	5360	3350	5280	1460
		HFC-236F	6940	8060	7400	8380
		HFC-245c	2510	716	1570	100
		HFC-245f.	2920	858	1970	121
		HFC-245c	6680	4620	6690	2410
		HFC-365n	2660	804	1890	114
	PFCs	CF4	4880	6630	5270	8040
		C2F6	8210	11100	8880	13500
		C3F8	6640	8900	7180	10700
		C4F10	6870	9200	7420	1100
		c-C4F8	7110	9540	7680	11500
		C5F12	6350	8550	6860	10300
		C6F14	5890	7910	6370	9490
	SF6	SF6	17500	23500	18900	28200

Table 8: Same as Table 7 for air pollutants, (based on IPCC, 2013, Collins et al, 2013)

Pollutant	reference	GWP				GTP			
		20		100		20		100	
		Europe	Global	Europe	Global	Europe	Global	Europe	Global
NOx	Fry et al, 2010; Funglesv	-39.4 ± 17.5	19	-15.6±5.8	-11	-48.0±14.9	-87	-2.5±1.3	-2,9
	Shindell et al., 2009		-108±35		-31±10				
CO	Fry et al, 2010; Funglesv	4.9±1.5	6 to 9.3	1.6±0.5	2 to 3.3	3.2±1.2	3.7 to 6.1	0.24±0.11	0.29 to 0.55
	Shindell et al., 2009		7.8±2		2.2±0.6				
NMVOC	Fry et al, 2010; Funglesv	18.0±8.5	14	5.6±2.8	4,5	9.5±6.5	7,5	0.8±0.5	0,66
BC	Fuglesvedt et al, 2010		1600		460		470		64
	Bond et al, 2013		3200 (270 to 6000)		900 (100 to 1700)		920 (95 to 2400)		130 (5 to 340)
OC	Fuglesvedt et al, 2010		-240		-69		-71		-10
	Bond et al, 2011		-160 (-6 to -320)		-46 (-18 to-92)				
SO4	Fuglesvedt et al, 2010		-140		-40		-41		-5,7
CFCs	CFC-11		6900		4660		6890		2340
	CFC-12		10800		10200		11300		8450
	CFC-13		10900		13900		11700		15900
	CFC-113		6490		5820		6730		4470
	CFC-114		7710		8590		8190		8550
	CFC-115		5860		7670		6310		8980
HCFCs	HCFC-22		5280		1760		4200		262
	HCFC-141b		2550		782		1850		111
	HCFC-142b		5020		1980		4390		356
others	CCl4		3480		1730		3280		479
	CH3Cl		45		12		15		2
	CH3CCl3		578		160		317		22
	Halon 1211		4590		1750		3950		297
	Halon 1301		7800		6290		7990		4170
	Halon 2402		3440		1470		3100		304
	CH3Br		9		2		3		0

3.3 The use of impact metrics in modelling

As indicated earlier, many modelling activities exist nowadays that consider simultaneously air pollutants and climate forcers, either in terms of emissions and/or concentrations (see also Table 9). Especially the EC-IMAGE and PEGASOS projects included the whole range of species. Both projects used radiative forcing (RF) metric to assess the impacts of these gases on warming in a common unit in the world, including Europe (see also Chuwah et al, 2013). The “EU Limits” project also used the RF metric to sum come the concentrations of different species, in order to assess the available emission space before achieving a global temperature increase of 2°C (Van Vuuren et al, 2014). Because of the long-term target, this study looked, however only at climate forcers and ignored the role of air pollutants. The TSAP study includes the (European) emissions of air pollutants and most climate forcers, and computed the concentration pattern of air pollutants throughout Europe (by using EMEP model). And the ECLIPSE project built upon TSAP projections to refine uncertainties on SLCP metrics, including GTP.

Table 9: overview of the metric use in the projects considered in this study

Project	Air pollutants considered	Climate forcers considered	Emission metrics	Concentration metrics
EC-IMAGE	X	X		RF
PEGASOS	X	X		RF
LIMITS		X		RF
TSAP	X	X	GWP	
CIRCLE		X		RF
ECLIPSE	X	X	GTP/GWP	

3.4 Summary and ways forward

In the previous sections different approaches were presented to express the contribution of compounds to climate change. These metrics were either concentration based (RF and ERF) or emission-based (GWP and GTP). All these approaches have been used to assess climate forcing up to now as well as for scenario studies up to 2100. These assessments show, for example, considerable effects on the shares of the species to the total GHG emissions in different countries, having consequences for the needed emission reduction (like indicated by Wang et al, 2013).
The advantage of concentration metrics is that they – by nature - can automatically be linked to *concentrations* and as such are very suitable to quantify the (long-term) role of atmospheric species to the climate system. The difficulty lies however in the retrieval of atmospheric concentrations from emission projection, which can be achieved in research projects by means of atmospheric chemistry and climate modelling, that can be subsequently translated into a CO_2 equivalent concentration (e.g. relevant in a policy context when aiming to limit the overall concentration below 450 ppm $CO_{2eq.}$, as done in the LIMITS project, van Vuuren et al, 2014). Effective radiative forcing (ERF) and Radiative forcing (RF) are significantly different for the anthropogenic aerosols and other short-living gasses, as the ERF concept allows rapid adjustments to perturbations of the Earth's surface and troposphere. Because of this consideration of these perturbations, the ERF concept is seen now as a more applicable indicator of the climate response of the atmosphere for these gasses (see also IPCC, 2013). As the ERF and RF values are quite similar for other compounds such as GHGs, RF is a more applicable metrics given that it requires fewer computational resources. Note that RF and ERF are still uncertain, as, among others, illustrated by different values between IPCC 4th (2007) and 5th (2013) assessments, especially for aerosols. When taking the 5% and 95% uncertainty ranges of the different forcers, the best estimate for the GHG forcing upon today is 2.3 W/m2 with a range between 1.1 and 3.3 W/m2 (Table 10). **Narrowing this uncertainty range is a major challenge in climate change research.**

Table 10: Best estimate values and 5 and 95% ranges for total forcing (source: IPCC, 2013). Note that the best estimate for aerosols shown here differs from the total given in Table 5. This is caused by: (i) that differences between ERF (this table) and RF (Table 5) are more visible for components that respond rapidly to changes in the atmosphere and surface characteristics – like aerosols; (ii) the different aerosol forcing shown in both tables. Here we show the total forcing of aerosols (including for example an indirect effect through cloud formation), whereas Table 5 depicts only the direct forcing on the radiation (which is about half of total forcing).

Forcers	Best estimate	5%	95%
Well-mixed greenhouse gases	2.83	2.26	3.4
Tropospheric & stratospheric Ozone	0.35	0.14	0.56
vapour	0.07	0.02	0.12
Land use	-0.15	-0.25	-0.05
BC on snow	0.04	0.02	0.09
Contrails	0.05	0.02	0.15
Aerosols	-0.9	-1.9	-0.1
Total	**2.3**	**1.1**	**3.3**

We presented GWP and GTP as two metrics suitable to compare the contributions to climate change of *emissions* of different components and regions/sources. These emission-based metrics are quite well available for many species, and as such very useful in policy assessments, when quantifying and communicating the contributions to climate change of emissions from countries or sectors. The main difference between GWP and GTP is that the former is integrated in time, whereas GTP is an end-point metric that is based on temperature change for a selected year. In other words, GWP integrates the forcing up to a chosen time horizon, whereas the GTP gives the temperature just for one chosen year with no weight on years before or after. In that sense, GTP somewhat analogous to

ERF, and GWP to RF. Different time horizons were presented for both GWP and GTP. The choice of metric and time horizon depends on the particular application, e.g. the policy context. When taking the long-term perspective of a 2°C target, metrics with long time horizons (GWP100 and GTP100) are more applicable as they emphasize the role of long-living gasses like CO_2 and N_2O. Rogelj et al (2014) showed that for such long-term targets short-living gasses bring only small benefits for limiting maximum warming, and as such emissions reduction measures for these gasses should be considered complementary rather than a substituting early and stringent mitigation of long-living gasses. And GTP100 emphasizes this role of long-living gasses more than GWP100.
When, however, the focus is on more the forcing over coming decades, like relevance in the European 20% emission reduction by 2020 or the 2030 energy package, synergies between short-living climate pollutants (SLCPs) and well-mixed GHGs become relevant. Under such assumptions, short-term metrics (esp. GTP20) proved to be more applicable (see also Tol et al, 2012, UNFCCC; 2012), as they include the warming due to short-lived emissions, whereas metrics that focus on longer time horizons exclude those effects. Again, GTP20 has shown to be more applicable than GWP20, as GTP includes more physical processes relevant for the interaction, where GWP does not consider these (IPCC, 2013).
Note that recent new metrics have been or are being developed, partly based on the original GWP and GTP concepts (IPCC, 2013). We mentioned some of these earlier in this chapter. Overall these new metrics have been applied only in few studies and some info (such as impacts and interactions between species, needed for the " Climate Change Impact Potential", and detailed growth information for the GWP_{bio} metric) is still lacking for these (Kirschbaum et al, 2014). There is also a strong concern on the uncertainties related to these metrics that were originally developed on the basis of a single Chemistry-Climate model (Shindell and Faluvegi, 2009) whereas multi-model ensemble is considered best practice in this field. Multi-model evaluation start to emerge in the literature (Collins et al., 2013; Shindell, 2012). Such study revisit the results of past coordinated model intercomparison projects (MIP) such as HTAP or ACCMIP. Their conclusions is however hampered by the fact that there has not been any specific MIP designed to address this issue of SLCP climate metrics so that the sensitivity of Chemistry-Climate models to Impulse Response Function is poorly documented (Olivié and Peters, 2013). **Before such an uncertainty assessment is conducted to propose some validation of the approach, using such metrics in a purely policy framework will remain exploratory. EEA could engage in supporting such uncertainty assessment, for instance by following the works undertaken in the new phase of HTAP.**

Many projects use global values for the metrics, whereas studies have shown that regional variability is large. There are isolated initiatives to derive regional metrics although the uncertainties remain large. Such uncertainties can be linked to multiple processes (e.g. yes/no climate-carbon feedback) and conditions (e.g. lifetime) that are involved, and the climate effect much depends on the emission location. Especially large ranges in GWP and GTP values are found for NOx. For some regions it is even hard to define whether NOx causes cooling or warming. This uncertainty is due to high reactivity of NOx and the many non-linear interactions operating on different timescales, as well as location-specific relevance of emissions and interacting processes (large heterogeneous emission patterns are shown for NOx) (Funglesvedt et al, 2010, Fry et al, 2012). As such, small updates in emission and concentration metrics could have considerable effects on the simulated current and future concentration. **Reducing the uncertainty in climate impacts of short-lived species at the regional scale is a high priority for future research to reduce the uncertainties in projecting overall GHG emissions.**

Furthermore, the spatial representation differs between what is available and what is potentially required to do risk assessments. Most climate change projects consider regional emissions and global average concentrations of most pollutants. However the rise of the mean temperature of a city can be 0–2°C (Zhou et al, 2014) or 3°C (Koomen et al, 2013) , or more warmer than its surroundings. For climate forcers urban increments are still lacking to derive the urban heat effect from global or regional studies.

4 Health and ecosystems

The evaluation of the efficiency of a given mitigation scenario in reducing the adverse impacts of anthropogenic activities on health and ecosystem can be divided in two steps. First the atmospheric concentration – and/or deposition – of harmful pollutants must be quantified. Then these quantities can be used to derive health and ecosystem impacts. Atmospheric concentrations are of course closely tied to primary anthropogenic emissions. But this relation is complex and non-linear because of the transport and transformation processes that occur in the atmosphere. In addition several harmful pollutants are secondary chemical species – such as ozone, but also a significant fraction of fine particulate matter. The importance of secondary aerosol to the PM_{10} mix over Europe is illustrated in the modelling results displayed in Figure 14. The colours of this map show which of primary anthropogenic, secondary, sea-salt, and desert dust dominate the PM_{10} mix over winter 2009. The intensity of the colour changes with the total load in PM_{10}. Whereas the contribution of primary PM can be large close to emission sources (hotspots and large conurbations), most of continental Europe is exposed to secondary particulate matter. Therefore, the present chapter is organised as follows: first we describe the various methodologies available to derived atmospheric concentrations from emission scenarios presented in Chapter 2, then we discuss the main steps required to derive health and ecosystem impacts before concluding on the available data and knowledge gaps.

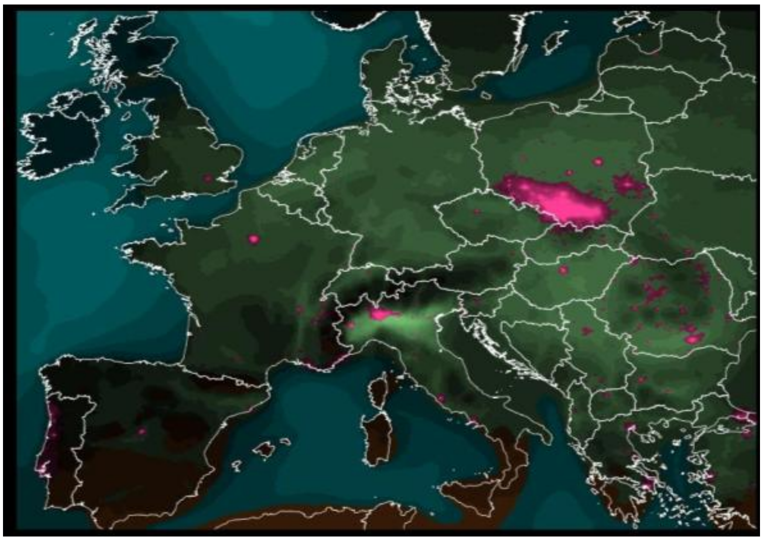

Figure 14: Typology of aerosol dominating the PM10 mix (pink: primary anthropogenic, green: secondary, blue: sea-salt, brown: desert dust) modelled by INERIS with the CHIMERE model for the winter of 2009.

4.1 Deriving atmospheric concentrations from emission scenarios

There is a wealth of techniques to model the change in atmospheric composition resulting from a given emission scenario, ranging from applying a simple multiplicative factor to full-frame chemistry-transport models. At the European level, the GAINS model plays a central role in supporting AQ policy evaluation. Besides the scenario and optimisation part, GAINS also includes an impact module that can assess health and ecosystem impacts of air and climate mitigation policies. Despite a few local implementation of GAINS, it is usually limited to the assessment of European scenarios. In order to help identifying the relevant tools when exploring alternative scenarios, possibly at a much finer spatial scale, we propose here an overview of existing surrogate modelling techniques. A paragraph is also included here to address the specific challenges related to the validation of such tools so that their relevance for policy applications can be ensured.

4.1.1 *Uniform conversion factor*

Building up on mass conservation principles, (De Leeuw, 2002) propose to estimate secondary inorganic PM formation using constant ratios applied to the emission of precursors. For instance, they argue that particulate sulphate ($SO4^{2-}$) can be approximated to about half the emission of SO_2 and nitrate would be 0.6 times the emission of NH_3 (see Figure 15). In doing so, they find quite a good agreement in comparison with Europe-wide deterministic Chemistry Transport Modelling. For organic aerosols, the performance of the approach is not as good. For ozone, the comparison of total burden over Europe is satisfying, but it is noted that the approach ignores the impact of long range transport and meteorological variability.

The main uncertainty of such uniform conversion factors regard their application at the local scale (since it was only validated for the continental average). It should also be noted that the complexity of PM modelling in CTMs (used for the validation) has increased substantially since then. But the simplicity of the approach makes it very appealing and worth further testing at the local scale against observations and more elaborate CTMs.

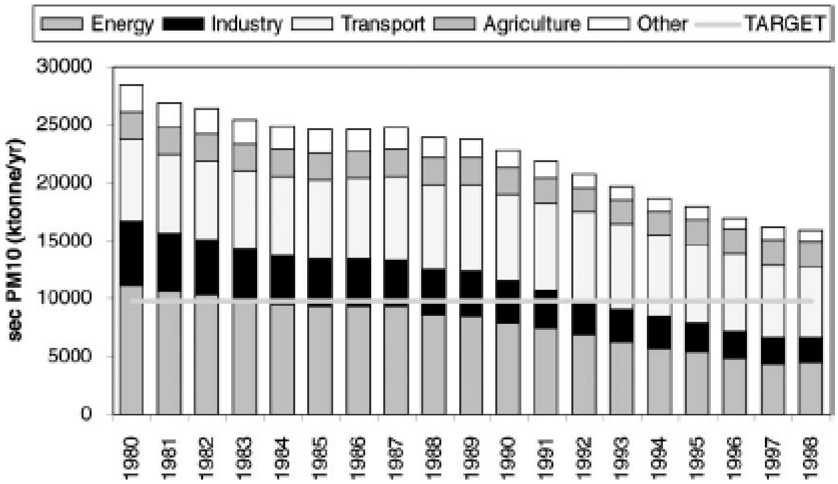

Figure 15: Aggregated emissions of precursors of secondary aerosol, totals for EU15 over the period 1980–1998; with the contributions of economic sectors (bottom), (De Leeuw, 2002).

4.1.2 *Source apportionment and zeroing-out*

Source apportionment aims at quantifying the relative contribution of given geographic origins, chemical species, or even activity sectors to the total concentration of pollutants. If we take the example of activity sectors, one may want to use the information provided by the source apportionment to estimate the efficiency of mitigation measures.

The general concept of model source apportionment consist in adding new species in the numerical chemical mechanism that would represent the source that the modeller wants to identify (geographical region or activity sector). The computational cost of such approaches increase with the number of species and sources to be investigated because of the multiplication of tagged species (as well as the multiplication of corresponding chemical reactions).

The main caveat of source apportionment regards the decision required to attribute to a given source the secondary formed product. Considerations on the chemical regimes can help in attributing O_3 formation to either VOC or NOx (see the OSAT implementation in CAMx (ENVIRON, 2002) and CMAQ (Xu et al., 2008)). But secondary aerosols are usually attributed to only one default precursors. In the widespread PSAT technique originally developed in CAMx (Yarwood et al., 2007), only NOx and SOx are considered to be responsible for secondary nitrate and sulfate formation, respectively (Cohan and Napelenok, 2011).

It is because of this approximation (attributing the formation of secondary pollutant to a single precursor) that source apportionment can be related to the zeroing-out approach. Zeroing-out consists in duplicating model simulations, removing 100% of the anthropogenic emission of a given

activity sector or region to estimate its impact on secondary pollutant formation. Even-though this approach was used in the past (Butler and Lawrence, 2009), it is now being consider as too uncertain because of the non-linear interactions between precursors. Such uncertainties are illustrated for instance by (Dennis et al., 2008) who discuss the impact of SO_2 emission reduction measures that can lead to the replacement of ammonium sulfate with ammonium nitrate.
The results of source apportionment and zeroing-out should thus be considered with care. If they allow to point out the main contributing sector/regions, the ultimate assessment of the efficiency of a mitigation measures can only be quantified by testing the scenario with a more elaborate approach (see below).

4.1.3 Sensitivity : incremental differentiation

Using perturbed emission input to assess the sensitivity of the modelled response to an incremental change of the emissions of an activity sector, a chemical precursor, or a geographic area is not a new idea (Roselle and Schere, 1995; Seigneur et al., 1981). It falls it the family of Empirical Kinetics Modelling Approaches (EKMA) that constitutes the basis for the well-cited isopleths of ozone productivity as a function of incremental VOC or NOx changes (Sillman, 1999). Using such sensitivity simulations, (Beekmann and Vautard, 2010) could propose European-wide maps of dominating ozone chemical regimes over Europe (Figure 16) that can be used to anticipate where NOx or VOC emissions should be targeted to efficiently reduce ozone levels.

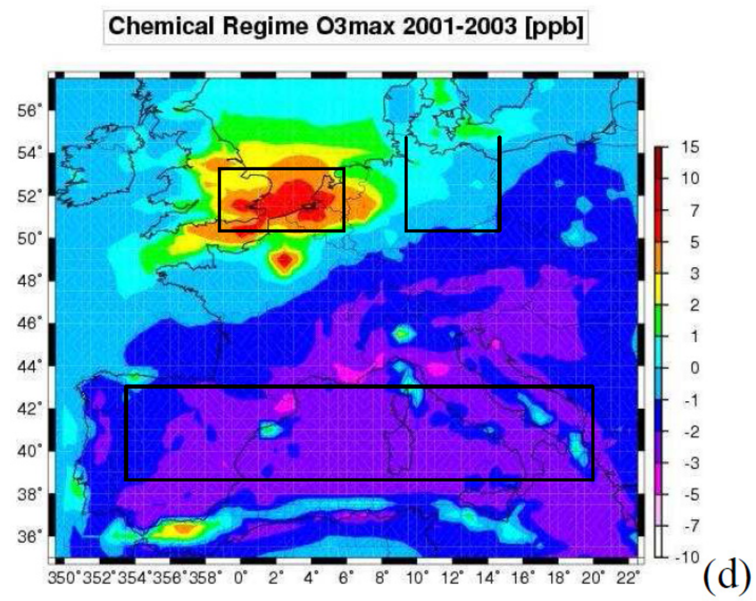

Figure 16: Ozone chemical regime map: difference between a 30% reduced NOx and a 30% reduced VOC emission scenario (Beekmann and Vautard, 2010).

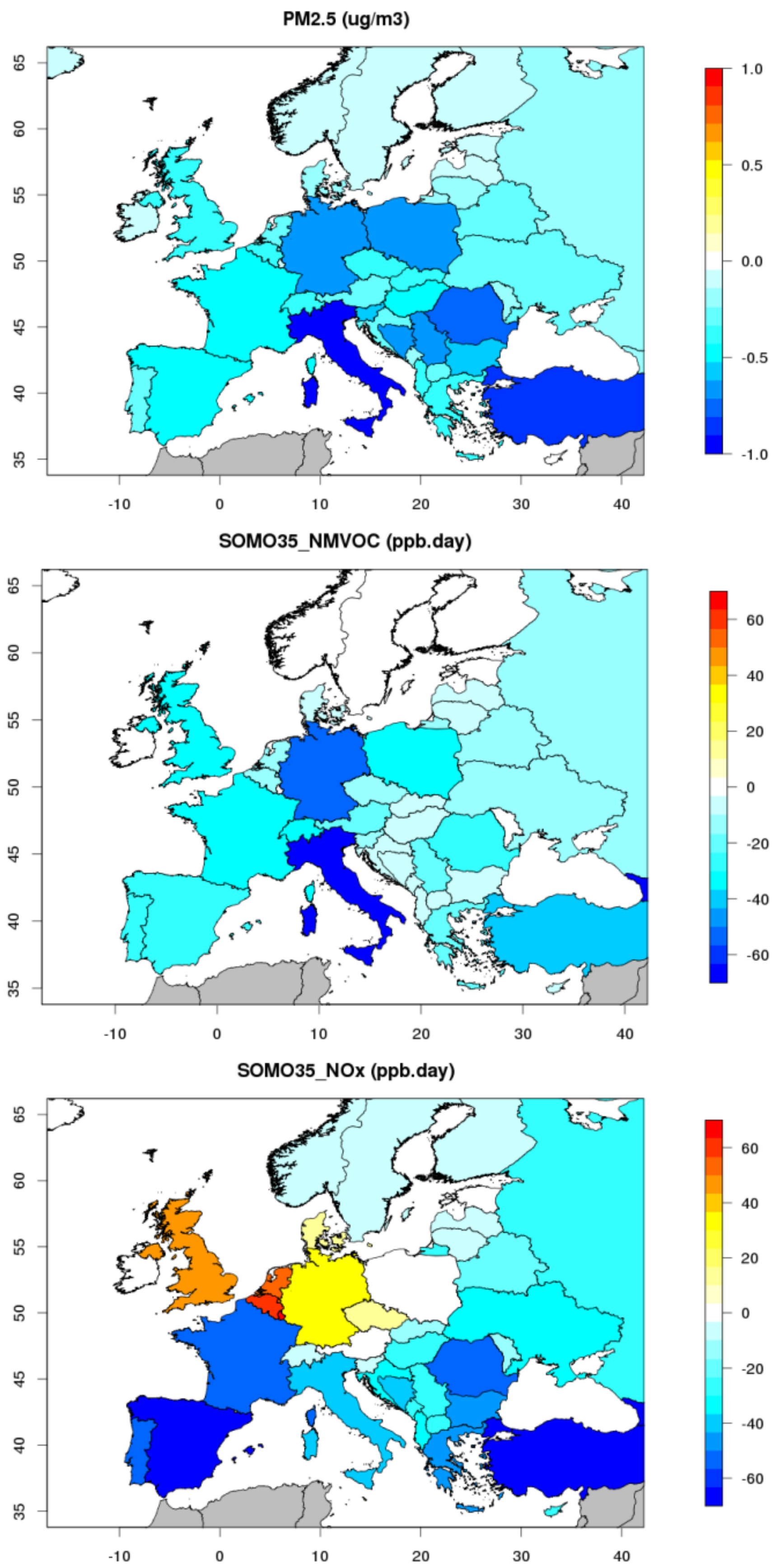

Figure 17: Maps of the EMEP country-to-country source receptor matrices showing the atmospheric response to an incremental change in emissions or the corresponding country. Top panel: PM2.5 response in the annual mean (µg/m3) to 15% reduction in all PM precursors. Lower two panels: SOMO35 response (ppb.d) to 15% reduction of either NMVOC or NOx emissions.

Building upon these sensitivity simulations, there a temptation to generalise the technique using a limited number of perturbed experiment that would subsequently be approximated with a simple analytical model. The main challenge regards capturing the interaction between multiple precursors across a wide range of emission changes. Such approaches are referred to as response surface modelling (RSM), surrogate, meta-model or model of the model.

The first-order RSM technique consist in realising a series of perturbed simulations with emissions changes typically 15 to 30% for selected activity sectors and geographic areas subsequently fitted with multivariable linear models. It is the approach underlying the Source/Receptor Matrices computed with the EMEP model embedded in the GAINS model (Amann et al., 2011; Heyes et al., 1996) which is very intensely used in support to air quality policy analysis in Europe. Similar approaches have also been tested in the US (US-EPA, 2006) China (Xing et al., 2011). An illustration such Source-Receptor Matrices (MSC-W et al., 2013)[8] is given in Figure 17 that displays the response of emission changes in every European country due to a 15% emission change in that country. Smaller responses indicates that the country is more sensitive to changes in mitigation policies being implemented beyond its borders.

Using a similar design of underlying ensemble sensitivity simulations, alternative techniques have been explored to avoid assuming a linear shape of the RSM. The main challenge in increasing the non-linearity of the RSM, and improving its robustness when extrapolating beyond emission changes explored in the learning sensitivity simulation, is limiting the size of the learning ensemble with regards to available computing resources.

- (Zhao et al., 2014) propose an Extended RSM, but the number of required simulations remains high (a few hundred for a given region). It has been tested at the scale of the Yellow River Delta.
- Using machine learning theory, (Carnevale et al., 2009) can reduce the number of simulations required to train a non-linear neural networks. This technique is underlying the RIAT+ Integrated Assessment Model, which is mainly used over local to regional pollution hotspots.
- Statistical Emulators also constitute a promising option. They consist in fitting the model response by means of non-parametric techniques based on a Bayesian approach (that relies on prior assumptions on the model behaviour). It has been used to compare the sensitivity of global chemistry-climate models to various type or processes or emissions (Carslaw et al., 2013; Lee et al., 2011; Lee et al., 2012) (Figure 18).

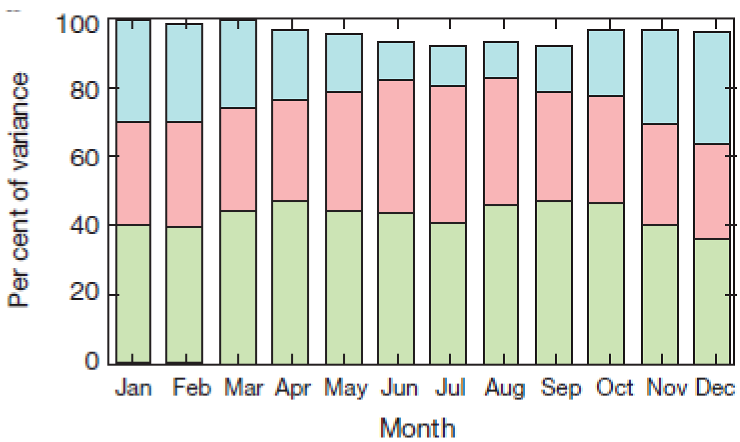

Figure 18: Seasonal cycle of the sources of uncertainty in global mean aerosol first indirect forcing. Contribution of different groups of parameters to global monthly mean forcing variance assessed using statistical emulators (green, natural emissions; pink, anthropogenic emissions; blue, aerosol processes) (Carslaw et al., 2013).

[8] Downloaded from http://www.emep.int/mscw/SR_data/Tables/2011_SRmatrices_R1Status2013AppC_Supp.tgz on 30/08/2014

4.1.4 *Infinitesimal differentiation*

The primary motivation to move from finite sensitivity analysis to infinitesimal differentiation lies in the fact that the linear approximation is more reasonable for small perturbation. That is why some authors attempted to estimate the sensitivity in the formulation of the model itself by differentiating the underlying system of equation.

Two types of techniques have been successfully tested for air quality purposes: adjoint modelling and Direct Decoupled Method (DDM). While the first is exhaustive in its exploration of the model parameters, but limited to a few receptor grid points, the second is valid across the modelling domain, but limited to a few pre-selected parameters.

Adjoint models have been developed in the past for several regional-scale CTM: CMAQ (Hakami et al., 2007), CHIMERE (Menut et al., 2000), EURAD (Elbern and Schmidt, 2001), STEM (Sandu et al., 2005), Polair (Quélo et al., 2005), CIT (Martien et al., 2006), and DRAIS (Nester and Panitz, 2006). However, all of these are limited to gaseous pollutant. An example of the use of adjoint modelling to investigate emission sensitivity in non-attainment area can be found in (Hakami et al., 2006).

The original DDM algorithm was first introduced as early as in (Dunker, 1981). It has been refined since by introducing a more computationally efficient DDM-3D approach (Yang et al., 1997), and extended to higher order differentiation in (Hakami et al., 2003) to better capture non-linear sensitivities. An example of its use for air quality policy assessment can be found in (Cohan et al., 2005). It remains however difficult to implement for particulate matter models.

4.1.5 *Full-frame chemistry-transport models*

Full-frame chemistry-transport models are generally used to inform the above mentioned simplified techniques. Sensitivity approaches are calibrated with a limited number of CTM realization and tested against out-of-sample simulations. Adjoint and Decoupled methods are based on simplified versions of the CTM.

Because of their computing cost, using such models to explore a wide array of scenario is challenging, even though the increase of computing power is such that it shall not remain prohibitive in the future. Such tools are already being used to explore limited number of scenarios and impact assessments. If we take the example of the use of the source-receptor matrices in GAINS, it is really for the optimization phase that fast tools are required. Once a limited number of scenarios are identified, their impact can be computed using full CTMs.

There is also an interesting junction between full CTMs and surrogate envisaged when increasing the complexity of the surrogate as in the (Zhao et al., 2014) example. If increasing the complexity of the surrogate model requires hundreds of CTM simulations, the opportunity to use directly the full CTM could be contemplated.

4.1.6 *Validation*

Similarly to AQ models, the capacity of surrogate response models in reproducing atmospheric concentration can be assessed. But evaluating their sensitivity is more challenging.

The most robust approach consist in testing the surrogate model against an out-of-sample full chemistry transport model sensitivity simulation. Using that approach, (Foley et al., 2014) found that their RSM captured better PM25 than DDM-3D, especially for large emission cuts (up to 30-90%) and PM_{25} (Figure 19). But this approach remains sensitive to the model used for training and testing the surrogate.

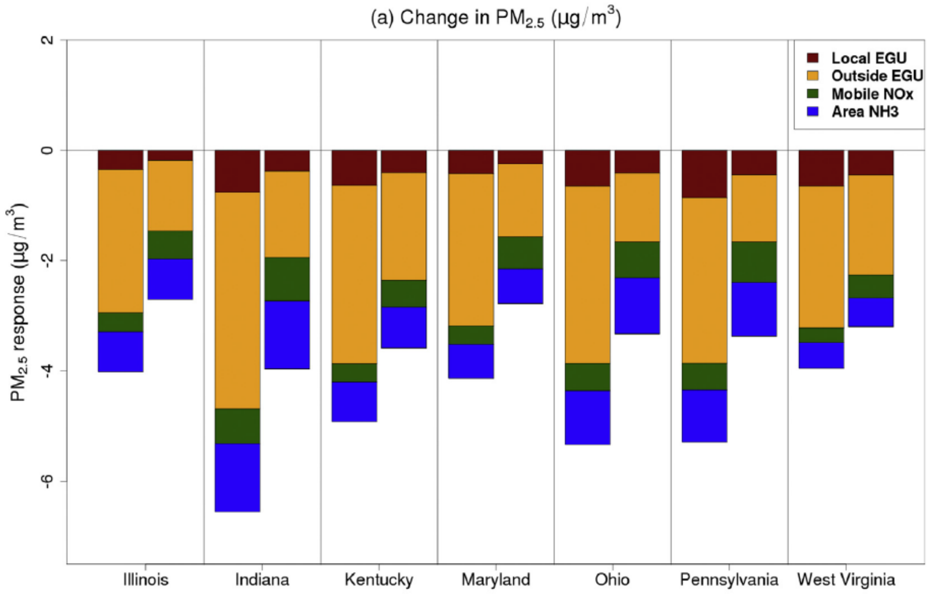

Figure 19 Population-weighted state-wide average change in PM2.5 due to 50% emission cuts in different sectors. Estimates based on the RSM are shown on the left for each state; DDM-3D-based results are on the right. EGU stands for Electricity Generating Unit (Foley et al., 2014).

The choice of the CTM used for the sensitivity simulations underlying the surrogate design can be assessed by comparing the response of ensemble of CTMs. In the framework of Fairmode, (Thunis and Clappier, 2014) proposed a new indicator – the potency – to compare the sensitivity of different CTMs to incremental changes in emission. Similar model intercomparison were performed as part of EuroDelta exercises (Thunis et al., 2007) to benchmark the sensitivity of the EMEP model (underlying GAINS SRMs) compared to other models. But such initiatives are limited to model intercomparisons and cannot involve measurements.

The surrogate models could also be benchmarked trough intercomparison exercise, although such endeavour where only tested in the US and China (Koo et al., 2009; Zhang et al., 2005; Zhao et al., 2014).

It is of course desirable to involved observation in such validation exercise, although it is not straightforward to relate emissions and concentrations using exclusively observations. Observation based source apportionment techniques such as Chemical Mass Balance (Chow and Watson, 2002) or Positive Matrix Factorisation (Reff et al., 2007) can provide an indication of the contribution of local/distant sources, or hypothetical emission sources even though they convey also a significant amount of uncertainty. Alternatively, more sophisticated observation of specific compounds that characterise chemical regimes is an option. Namely, the O3/NOy or H2O2/HNO3 ratios can provide relevant information for the O3 formation mechanism (Beekmann and Vautard, 2010). The g ratio of free ammonia to total nitrate can help distinguishing if nitrate formation is limited by NH_3 or NOx availability (Bessagnet et al., 2014).

Last, dynamical validation is an option. By testing the RSM against observations under changing conditions: e.g. comparing weekdays to weekends, before/after the implementation of major control policies, or over long time periods. The major caveats of all these techniques regards the confidence in the input emissions, that add up to the uncertainty of the RSM. The Eurodelta-trend exercise initiated in 2014 under the auspices of the CLRTAP Task Force on Measurement and Modelling could provide the basis for a sound benchmark of the CTM response to emission changes over the past 20 years, and therefore contribute in testing the surrogate ability to respond to large emission changes.

4.2 Health and ecosystem impacts

Once atmospheric air pollutants concentrations have been estimated from anthropogenic emissions, they can be mapped over population density or ecosystems maps to assess the exposure. Dose-response relationships allow in turn to estimate impacts.

4.2.1 Health impacts

Synthetic indicators such as annual mean $PM_{2.5}$ or SOMO35 (sum of daily max ozone over 35ppb over a year), have long been used as proxies for health impact of air pollution but it is desirable to have a more quantitative assessment of the mortality or morbidity impacts.

There is a wealth of epidemiologic work being conducted to improve the knowledge of the relative risk of given health endpoints that can be attributed to air pollution. The World Health Organisation conducted two important projects in 2013 to review the state of knowledge on the risk posing on human mortality and morbidity from air pollution (HRAPIE and REVIHAAP, (WHO, 2013a, b)).

The challenges lie in using the appropriate relative risk function for the selected pollutant and health end points. Specifically, there are large uncertainties for very high exposure areas (where underlying epidemiological evidence is scarce), although this limitation mainly applies in highly polluted areas of Asia.

In addition to risk functions, information is needed on the baseline incidences of the selected health endpoint (mortality, morbidity) and demographic data. At the European level, health data at the national level is available from the WHO (2013). Population data, including gender and age distributions are available for the current situation as well as for the years up to 2100 (with a five-year resolution, under different population scenarios) from the UN (2012). High resolution data on population densities are available from the ETC-ACM task 1.1.2.2.Spatial air quality assessments. The population map is mainly based on the work from JRC (2009). Securing high-quality spatializedspatialised population data is also an issue. It should be noted that such information should include mortality and life table, besides population density. The future evolution of such data should also be taken into account, even though for the sake of limiting uncertainty, population is sometimes kept constant in such analyses, e.g. the cost benefit analysis supporting the recent TSAP revision (Holland, 2013).

The relative risk related to $PM_{2.5}$ and ozone exposure for the population living in a certain area with a concentration C is usually estimated with a log-linear response :

$$RR = \exp[(\beta/10) \cdot (C - C_0)] \qquad [1]$$

where β is the given coefficient risk factor, see the HRAPIE-report from WHO (2013). So that for instance, a 10 $\mu g.m^{-3}$ change in $PM_{2.5}$ leads to 6% change in risk, while a change of 20 $\mu g.m^{-3}$ will lead to a change in risk of 12%.

The attributable fraction, AF, (i.e. the attributable risk among the exposed population) of a health effect from exposure to an air pollution component is estimated by the standard formula (see e.g. Perez and Kunzli 2009):

$$AF = (RR - 1) / RR \qquad [2]$$

The expected health impact attributable to air pollution is given by:

$$E = AF \,.\, MR.\, Pop \qquad [3]$$

where E is the expected burden of disease (e.g. number of premature deaths due to ambient air pollution;

MR is the population incidence of the given health effect (i.e. non-violent deaths per 1000 people per year); and Pop is the relevant exposed population for the health effect (e.g. adults older than 30 years or the total population).

The total impact on human health in a country j is now obtained by:

$$I_{comb,j} = E_{PM,j} + E_{O3,j} \qquad [4]$$

where $E_{PM,k}$ and $E_{O3,k}$ are health impacts attributable to $PM_{2.5}$ and ozone exposure, respectively.

Conceptually, the impact assessment framework remains based on log-linear RR function that are much less complex than the computation of air quality response to emission changes. The robustness of this log-linear approximation is being questioned in highly polluted areas of the world (such as Asia), but its validity seems well established over Western countries. A more substantial knowledge gap lies in the availability of high resolution population maps, and more importantly high resolution baseline mortality (noted MR above) that is generally difficult to secure at the sub-country level.
For more details, the reader is referred to task 1.1.2.2 of the 2014 AP that is focused on health impact mapping.

4.2.2 Ecosystem impacts

Similarly to health impacts the AOT indicator has long been used as a proxy for ecosystem impacts. It is based on the cumulated surface ozone atmospheric concentration over a given threshold and time period (that depend of the ecosystem of interest) (EEA, 2009). Similarly, deposition of eutrophying compound can be cumulated over a given period and compared to the critical load acceptable for various types of ecosystem.
A more mechanistic indicator is sometimes favoured, in particular by the International Cooperative Programme on Effects of Air Pollution on Natural Ecosystems and Crops of the CLRTAP Convention: the Phytotoxic Ozone Dose (POD). It based on the cumulative stomatal flux of ozone that better captures the impact of ozone on the plants. It's evaluation requires crossing high-frequency ozone time series (typically hourly), with information on the phenological activity of the plant (diurnal and seasonal). It can also include an information on the external stressors bearing upon the plants (such as the temperature and water stress). POD can subsequently be translated in terms of yield losses for crops using linear relative risk functions. An illustration of such a PODy map for wheat crops computed with the Chimere model is displayed in Figure 20.

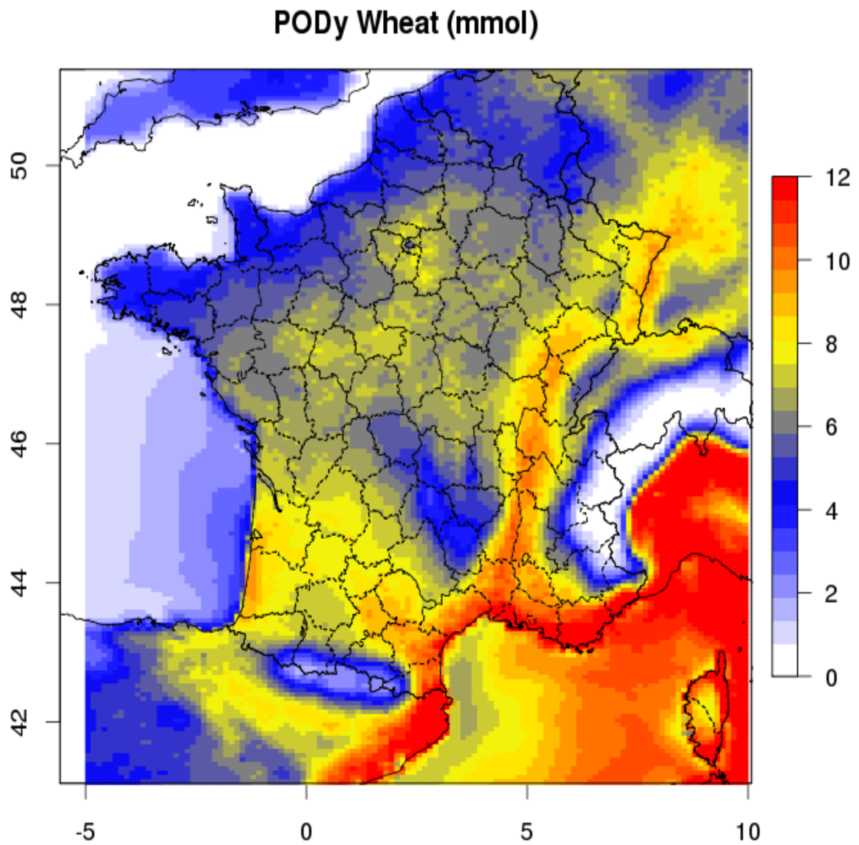

Figure 20: Phototoxic Ozone Dose (POD6) for wheat computed with the Chimere model over France.

The detailed methodology is described in the ICP Mapping Manual[9]. The requirement to use high-frequency ozone time is a serious limitation for its use in conjunction with surrogate air quality models that general lack such a fine temporal resolution. In addition, detailed information on crop location, nature, and growing season is required. Whereas the location agricultural lands are readily available in mainstream landuse databases, computing the POD, requires an information on the type of crops, which can be available for given countries (such as France in the example of Figure 20), but more challenging to retrieve over the whole Europe.

[9] http://icpvegetation.ceh.ac.uk/manuals/mapping_manual.html

4.3 Summary on the availability of tools and input data

Quantification of atmospheric concentrations :

The complexity of chemical processes occurring in the atmosphere make it difficult to derive concentration of pollutants (many of which are secondary) from primary emissions. There is a temptation to limit the analysis to primary emitted compounds, but considering that a large fraction of the PM load in Europe is secondary (Figure 14), and that ozone is a purely secondary pollutant, the risk is high to ignore essential processes. The most exhaustive technique to assess the response of atmospheric concentrations to a given change in air pollutant emissions consist in using a full frame CTM. The computational cost is however such that alternative approaches have been proposed. Their relative strength and weaknesses are summarized in Table 11 as well as an indication on the availability of the models.

Considering that atmospheric concentrations can only be related to the emissions of air pollutant by taking into account transport and transformation processes occurring in the atmosphere, the alternative surrogate modelling technique all rely to some extent on full frame chemistry transport modelling. Atmospheric concentrations – as modelled with a CTM – can be fitted to absolute emissions (uniform multiplicative factors), or relative changes in emissions (incremental differentiation). An infinitesimal differentiation of the CTM is used to build adjoint and decoupled surrogate models. And individual contributions are tracked in the CTM for the source apportionment and zeroing-out methods.

Table 11: synthesis of the main strength and weakness of existing techniques to assess the impact on atmospheric concentrations of air pollutant emission scenarios.

Method	Strength	Weakness	Availability
Uniform multiplicative factor	• Simplicity	• Outdated and not validated against recent evidence	• Only for sulphate & nitrate • Lacking for other secondary PM, and for O3
Source Apportionment & zeroing out	• Contribution of pre-identified regions/sources • More relevant to design scenarios than assessing their impacts	• Ignore non-linearity and/or combination of source, either on the overall result (zeroing out), or at each integration step (source app.)	• Implemented in CAMx, CMAQ, partly in LOTOS
Incremental differentiation	• Robustness and conceptual simplicity	• Limited to the range of perturbation and geographical area of the calibration dataset • Require additional downscaling if trained on continental area	• At European scale : GAINS. • At higher resolution : available for selected areas with the RIAT+ tool (North of Portugal, North of Italy, Eastern France)
Infinitesimal differentiation	• Does not require costly training datasets	• Conceptual complexity, requires developing a simplified CTM	• Mostly used in the US and China (CMAQ & CAMx).
Full-frame Chemistry-Transport Model	• Exhaustive	• Computational cost if the aim includes optimising scenarios • The cost can be manageable to explore a limited set of scenario and impacts	• Several tools in use in Europe and beyond

Amongst the above tools, those that can be implemented to explore the air quality impacts of a given air and/or climate policy scenario are:

- Uniform multiplicative factor: no matter how crude that approach seems, it could be found quite efficient and would deserve being revisited on the grounds of new evidence.
- Incremental differentiation: such tools are well suited for the purpose. The spatial coverage remains a bottleneck, with GAINS being only relevant at the European scale (although some national version are developed) and RIAT+ being only relevant for selected subregions. In addition, there is no “standalone” version of the impact modules of such integrated assessment models. Such that it is technically difficult to use them to assess the impact of an independent emission scenario.
- Full frame Chemistry-Transport: the only drawback of this method lies in the implementation cost. While the computing costs decrease gradually, the difficulty to implement a CTM over the area of interest remains.

The other approaches (infinitesimal differentiation, source apportionment) are really focused on the assessment of the sensitivity of the atmospheric system. They can be used to point out which chemical compound contributes most to the degradation of air quality, or which compound would be the most efficient in improving AQ. But they can not readily be used to explore emission scenarios.

Health and Ecosystem impacts:

The assessment of health impacts is less challenging on a methodological point of view than deriving the exposure to atmospheric concentration of air pollutants resulting from a given change in primary emissions. The only substantial uncertainty regards the linearity of the relative risk function, although this hypothesis is usually considered reasonable for the range of air pollution exposure in Europe (this hypothesis is less robust in the developing world). The main bottleneck lies in the availability of input data. While present-day consistent European datasets on total population numbers and baseline mortality information are available at the national level, their downscaling health data at high resolution and projecting their future evolution requires further work. Consistent downscaling of population density is being undertaken in a dedicated ETC task (1.1.2.2). This exercise is based on the current (2002) population distribution; it does not account for further urbanisation which might increase the uncertainties in future scenarios. Moreover, in the downscaling it is assumed that the age distribution is uniform over the country which will also introduce an (unknown) uncertainty. A consistent database with regionalised baseline information on selected health endpoints is lacking, further work has to be done here.

As far as impacts on agriculture are concerned**,** consistent pan-European databases of crops location, typology and growing seasons are the key missing input data to improve the robustness of the assessment.

4.4 Ways forward

Using uniform multiplicative factors may seem over-simplified but this simplicity is appealing enough to seek a revision of such approaches and assessment against more complex tools.

The **common limitation of surrogate models based on incremental differentiation is their lack of universality** since they must be recalibrated over each new area they are applied to in order to account for local specificities. There are current alternatives to overcome this difficulty by using coarse sensitivity simulations in addition to innovative downscaling techniques (Kiesewetter et al., 2014) or improving the resolution of the sensitivity simulations.

The question of **dynamical evaluation of surrogate models and underlying CTMs is also a matter of concern**. A benchmark of the sensitivity of existing CTMs to incremental changes in emission was proposed in the second EuroDelta exercise (Thunis et al., 2007). Such approaches have however never been validated with measurements, the forthcoming EuroDelta-Trends exercise will provide an unique opportunity to assess their efficiency in capturing emission changes over the past 20 years. Designing an appropriate validation framework for surrogate models raise difficult scientific questions. Such questions should however be addressed, given the implication of using un-validated tools in support to policy making.

Regional-scale assessments are often performed with a spatial resolution of 50 km × 50 km. Most impact studies, however, prefer a much finer spatial resolution. Any assessment with a 50 km resolution may systematically underestimate higher pollution levels in (European) cities (EUclimit, 2013). Solutions have been found in the form of a scaling factor that quantifies the increments in pollutant concentrations in urban areas as part of the CAFE and TSAP programmes (Amann et al., 2011; Kiesewetter et al., 2014) and the EUclimit project (EUclimit, 2013).

As far as health and ecosystem impacts are concerned, one should refer to the substantial work being conducted elsewhere in the ETC Action Plan. **Key priorities in consolidating input data include improving the high-resolution downscaling of population density and baseline mortality as well as crops location, typology and growing seasons**. As far as methodological improvement are concerned, research is ongoing in the epidemiological community to better identify the key PM compound playing a role on human health. Identifying whether such compound can be related to total PM, black carbon, or BaP (which is very much correlated with the use of wood burning for residential heating) can have strong consequences on the link with the climate impacts of such compounds emission sources.

5 Synthesis & possible methodologies for improvement

Taking into account air quality and climate change in an integrated manner raises a number of challenges. The present report reviewed some of the key issues to be improved in the future as per data and knowledge gaps. Quantitative emission models that can be used to translate mitigation measures into greenhouse gases and air pollutant fluxes were presented in Section 2 with a focus on the models and scenarios where air quality and climate are jointly considered. The available methods to translate, in turn, such emission scenarios in terms of either climate or air quality impacts are presented in Sections 3 and 4, respectively. In the present section a synthesis of the main findings for each section is proposed as well as a discussion of cross-cutting issues.

5.1 Emissions Projections

The knowledge and methodological challenges related to emission projections can be split between conceptual/design issues and more technical points.

The main issues related to the design of the scenarios regards the fact that most scenarios start with a climate context, on top of which are added air quality policies. This is due to the fact that energy production is the most structuring activity sector for future projection, hence the strong link with climate policies. It would nevertheless be interesting for EEA to design scenarios with a primary air quality concerns, and investigate the additional cost of climate policies.

Another conceptual issue induced by present knowledge gaps is the general **lack of non-technical measure in quantitative projections**, whereas there is a large scope for both air pollution and climate mitigation in structural measures (taxing pollution, reduced meat consumption, efficient use of heating in houses, alternative city planning,...). It is proposed that EEA considers to include non-technical/structural measures in one of the next scenario studies on climate and air quality interactions.

Global scenarios often have a limited spatial representation of the EU (a few regions). European assessments requires a spatial resolution of national scale and in some cases down to gridded/agglomerations. **Proposal is for EEA to further develop methods to downscale emission data. A few Institutes such as TNO or INERIS have developed expertise in producing high resolution (7km) top-down inventories. INERIS also proposes to make the best of national bottom-up inventories (sometimes up to 1km) being developed at the national level, for instance by using them as proxies, yet remaining consistent with officially reported national totals.**

In the more technical issues, we find the inconsistency between chemical species included in climate or air quality scenarios. **Nitrogen has important co-linkages, but is often overlooked in climate scenarios**, this is especially the case for agricultural emissions, and their impact on ecosystem (C/N ratio, critical loads) and health (PM_{10}) impacts. The lack of information in NH_3 emissions for climate projection is due to the fact that past climate model ignored the complex role of ammonia in formation of secondary inorganic aerosol. That is why little efforts are devoted to projections of ammonia emissions in climate models whereas they are needed to assess the nitrate and sulphate aerosol concentration and their effect on the climate system. This situation is gradually changing with the improvement of aerosol chemistry in climate models.

5.2 Climate Impacts

Climate impacts metrics can be split in two families. GTP and GWP are applied directly to emissions (and are therefore relevant to assess the impact of emissions scenarios and policies). There are also metrics that are applied to concentrations (ERF and RF) and are therefore relevant for present-day assessment, or when used in conjunction with a chemistry-transport or surrogate atmospheric model.

Whereas climate metrics based on the concept of radiative forcing at equilibrium such as RF and GWP are robust for well mixed, long-lived compounds, knowledge is still fractional when it comes to short-lived compounds. The most relevant metrics for long-lived species are radiative forcing (RF) or GWP. But for short lived compounds, ERF and GTP are more relevant since they account for the limited chemical lifetime of the species and the long-lasting perturbation they convey to the atmosphere. We conclude that **GTP is a more applicable indicator of the climate response of the atmosphere for synergies than RF and GWP, especially for short-term assessments where SLCP are relevant** (see also Tol et al, 2012, UNFCCC; 2012).

The main conceptual difficulty lies in handling regional specificities given that the climate impact of SLCPs might differ depending of the location of the source. Largely because the species will react differently (therefore have different lifetime and reaction products) according the location and abundance of other co-emitted compounds. **Regional climate metrics exist in the literature and further work to reduce uncertainties of such metrics should be supported**. The Eclipse FP7 project should contribute to this aim, but we are still missing a dedicated Model Intercomparison Exercise, focusing on benchmarking the climate response of a range of models to frame the uncertainty of Impulse Response Functions (Olivié and Peters, 2013). Would such an exercise be initiated, the EEA could contemplate engaging as a stakeholder. There is also a possibility that the ongoing new phase of HTAP could serve this purpose.

There is also the issue of defining the appropriate time (20, 50 , or 100 years) scale depending on the target of the assessment. This choice of the time horizon depends on the application, e.g. the policy context (i.e. long-term target, or 2030/2050 emission reductions).

Last, the possibility to make use of urban increments analogous to those used for health impacts, but to capture possible changes in the urban heat effect could be considered.

5.3 Health and Ecosystem impacts

The main challenge when assessing health impacts in relation with air and climate policies lies in the evaluation of atmospheric concentration of pollutants resulting from the emission of pollutants and precursors. The secondary nature of key compounds such as ozone, and the important contribution of secondary aerosol to the PM mix constitutes an substantial barrier.

In order to avoid implementing complex and costly full-frame chemistry transport models, various types of surrogate air quality models are used. Such surrogate range from simple scaling factors, to statistical model trained on sensitivity CTM simulation (such as in the GAINS model trained on EMEP source-receptor matrices) and adjoint and decoupled methods. **While there are well established tools to assess the air quality response of emission scenarios at the European scale, the availability of surrogate models at the scale of a given country or subregion is an issue**. There is a variety of techniques available to develop such tools, their implementation is more a problem of resources than knowledge gap. The future development of a myriad of such tools over isolated areas will however inevitably lead to a problem of consistency. **EEA could play a role in ensuring such a consistency, starting with the issue of taking into account both climate and air pollution mitigation and impacts in an integrated manner.** The EU is also calling for the development of such framework, e.g. through an H2020 call open in 2015. The EEA could contemplate entering in the stakeholder board of the winning bid to make sure that key questions highlighted in the present report are addressed. The more conceptual challenge of building high-resolution tools valid across a large geographical area should be addressed. There are also little opportunities to benchmark these tools, which are extensively used in support of policy making. **Given the stake of air and climate mitigation, model intercomparisons and dynamical evaluation exercises are critical to guarantee the robustness of models used to support policy. Such an exercise will be for instance performed as part of the Eurodelta exercise in support of the TFMM and EEA could consider following and support such initiatives**.

Assuming exposure (air concentration) fields are well established as per the techniques described in the earlier paragraph, there are still issues with data availability for the health and ecosystem impact assessment. In particular, securing life table and mortality databases at the sub-national granularity is desirable. **Concentration-response functions are also lacking for individual particulate matter compounds, challenging the assessment of the impact of policies targeting specific activity sectors** (agriculture with ammonia emissions, domestic would burning and BaP). When it comes to impacts of pollution on agricultural yields, assessing the vulnerability of crops in a realistic environment is challenging since most dose-response relationships are derived from limited experiments and difficult to extrapolate. Better information is also required on the crop composition, location and growing cycles at the European scale.

5.4 Cross cutting issues

Between the climate and the Air Quality modelling community different metrics exists for the same component. E.g. total tropospheric ozone column (expressed in Dobson units) in the Climate change community, while the health and ecosystems impact requires ozone to be expressed in SOMO35, AOT40 or POD at ground level. There is no direct link between tropospheric ozone columns and surface concentrations, challenging the integration of air and climate issues, even for a well studied chemical compound such as ozone. **It is not relevant to attempt to relate surface and column concentrations, although this difficulty should be kept in mind.**

There are inconsistencies between the atmospheric compounds included in air quality and climate impacts projects. Assessments **focused on the issue of air pollution and impact on health (e.g. TSAP) include total PM, whereas a distinction between BC and OC is needed to quantify the climate forcing**. Similarly, non-carbonaceous primary PM is generally overlooked in climate emissions because of their minor role in the radiative forcing, whereas they carry substantial impacts on health. **The details available in emission scenarios are gradually improving, so that a better integration between climate and air quality issues can be proposed.** Table 12**attempts to summarise the focus of recent large European projects and relation to mainstream scenarios projection in order to highlight this integration. By being part of stakeholder board of such projects, EEA could ensure that this Table is better filled in the future.**

Table 12: Summary of the focus of recent large European projects and their relation to mainstream scenarios projection in order to highlight the integration between air pollution and climate change issues

Project	Scenario family	Air Quality			Climate			
		Pollution	Health	Ecosystems	RF	ERF	GWP	GTP
EC-IMAGE	RCP	X			X			
PEGASOS	RCP	X			X			
LIMITS	RCP	X			X			
CIRCLE	RCP							
TSAP	TSAP		X	X			X	
ECLIPSE	TSAP	X					X	X
ECLAIRE	TSAP			X				

5.5 Way forward

The Climate Change community has clearly improved in assessing interlinkages between air quality and climate change issues going from AR4 (2007) to AR5 (2013). There exist now a rich variety of scenario's, based on the RCP scenario's, that describe the effect of Climate Change (policies) on air quality and vice versa. For recent scenario's directed at Air Quality policies, such as the TSAP scenario's, less progress is seen, interlinkages with Climate Change are limited to the effect on the GHG emissions. In this report data and knowledge gaps were identified and ways forward to improve these have been proposed. The next step forward is to discuss these issues with the research community. One way of achieving this is by organizing a workshop to discuss these issues and put in perspective the findings of the report to investigate in more details:

i. the identified data and knowledge gaps and get a response of the experts in this field on this assessment;
ii. propose a strategy to close identified information gaps;
iii. recommend short and long term actions to improve the assessment of Air Quality-Climate Change interactions.

By picking up those issues that will impact the quality of EEA work where the role of air-climate interlinkages needs to be shown/evaluated, such a workshop should help to identify:

- the main actions and actors that can advise the EEA how to move forward on the topic;
- suggestions for the research community on how to support the science-policy link on air climate issues.

5.6 Synthesis Table

The main bottleneck in considering jointly Air Quality and Climate Change in integrated assessment are synthesized in Table 13.

Table 13: Bottleneck issues and proposed actions in case of joint consideration of air pollution and climate change in integrated assessments

	Issues	Proposed Actions	Potential Actors	Ongoing or recent project addressing the issue
Prospective scenarios	Availability of quantitative emissions of both greenhouse gases and air pollutants in prospective scenarios	• Rely on up-to-date emission factors for air pollutants in climate projections • Include a variety of air pollutant policies in climate projections, and a variety of climate policies in air quality projections • Be comprehensive on the list of targeted chemical compound (e.g. include F-gases in AQ projections, and include NH_3&PPM in climate studies in addition to BC&OC)	PBL IIASA	PEGASOS, ECLIPSE
	Focus limited to technical measures	• Include non technical measures		No significant advance
	Inconsistency in the spatial scale of (global) climate and (local) AQ scenarios	• Prospective scenarios are usually developed at the country or continental level and need to be downscaled spatially to be relevant for air quality studies	TNO INERIS IER	MACC, EC4MACS
Climate metrics	Reduce uncertainties for emission (GTP) or concentration (ERF) response metrics	• Multi-model evaluation of metrics at the regional level	Global chemistry Climate modellers (e.g. CICERO, Met Office,…)	ECLIPSE, HTAP-2
Air Quality Impacts	Need to assess the performance of surrogate models being used in support to policy to explore air and climate scenarios	• Design a validation framework for sensitivity models.	JRC, IIASA, TFMM	EURODELTA3 phase 2 (Trends)
		• Benchmarking of existing tools (GAINS, FASST, RIAT+, direct decoupled methods, source apportionment…)	IIASA, JRC, Univ Brescia, ...	No relevant ongoing action
	Lack of universal model valid from the city to continental scale	• Promote best practices to avoid inconsistencies between local and continental assessment and between individual cities • Encourage the development of pan-European city-scale models	EEA	
Health and Ecosystems	Concentration response function	• Improve vulnerability functions for individual chemical compound, or individual health end point and ecosystem typology	Health and Ecosystem impact experts	REVIHAAP, HRAPIE
	Exposure	• High resolution population and baseline mortality data • High resolution crop databases over europe		

Annex 1: Models used for the preparation of scenarios

Introduction

Assessments through the use of scenario's are largely dependent on the models used to construct these scenario's. In this annex the models used in the scenario's assessed in this report are shortly summarized. Some of these descriptions have appeared earlier in Eerens & van de Brink, 2013[10].

Model	Organisaton	Location	Classification	EMF-27*
POLES	Joint Research Centre Institute for Prospective Technological Studies	Spain	EU-Country	+
	Université Pierre-Mendès-France (UPMF)	France		
PRIMES	National Technical University of Athens (NTUA)	Greece	EU-Country	
GAINS	IIASA - International Institute for Applied Systems Analysis (IIASA)	Austria	EU-Country	
GEM-E3	Joint Research Centre Institute for Prospective Technological Studies	Italy	EU-Country	
	National Technical University of Athens (NTUA)	Greece		
	Katholieke Universiteit Leuven (KU Leuven)	Belgium		
	Budapest University of Economic Sciences (BUES)	Hongary		
TM5	Joint Research Centre Institute for Environment and Sustainability	Spain	EU-Country	
	Royal Netherlands Meteorological Institute (KNMI)	Netherlands		
EMEP	European Monitoring and Evaluation Programme (EMEP)	Europe	EU-Country	
CHIMERE	L'Institut National de l'Environnement Industriel et des Risques	France	EU-Country	
CAPRI	University of Bonn	Germany	EU-Country	
TREMOVE	Transport & Mobility Leuven	Belgium	EU-Country	
ENV-Linkages	Organisation for Economic Co-operation and Development (OECD)	France	EU-Country	+
FASST	Joint Research Centre Institute for Prospective Technological Studies	Italy	EU-Region	
ECHAM5-MESSy	Max Planck Institute for Meteorology	Germany	EU-Region	
	Max Planck Institute for Chemistry	Germany		
EC-IMAGES	Royal Netherlands Meteorological Institute (KNMI)	Netherlands	EU-Region	
E3MG	Cambridge Econometrics	United Kingdom	EU-Region	
WITCH	Fondazione Eni Enrico Mattei (FEEM)	Italy	EU-Region	+
GCAM/-IIM	Joint Global Change Research Institute, University of Maryland	United States	EU-Region	
	Indian Insitute of Management (IIM)	India		
IMAGE/TIMER/FAIR	Netherlands Environmental Assessment Agency (PBL)	Netherlands	EU-Region	+

[10] Internal PBL note (2013) on the use of models in integrated assessments, in Dutch.

Model	Organisaton	Location	Classification	EMF-27*
MERGE-AIR/MERGE	Netherlands Environmental Assessment Agency (PBL)	Netherlands	EU-Region	+
	Netherlands Bureau of Economic Policy Analysis (CPB)	Netherlands		
	Economic Policy Research Institute (EPRI)	South Africa		
WORLDSCAN	Netherlands Bureau of Economic Policy Analysis (CPB)	Netherlands	EU-Region	
GTAP	Purdue University	United States	EU-Region	
MAGNET	LEI Wageningen Wageningen University	Netherlands	EU-Country	
COPERT	Joint Research Centre Institute for Environment and Sustainability	Italy	EU-Country	
EU-FASOM/DNDC	University of Hamburg	Germany		
CCE-Impact	National Institute for Public Health and the Environment	Netherlands		
Alpha-2	Metroeconomics	United Kingdom		
	Ecometrics Research and Consulting (EMRC)	United Kingdom		
	AEA Technology	United Kingdom		

*) EMF27 Stanford Energy Modeling Forum Study 27 was driven by a model inter-comparison of 18 energy-economy and integrated assessment models. The study investigated the importance of individual mitigation options such as energy intensity improvements, carbon capture and storage (CCS), nuclear power, solar and wind power and bioenergy for climate mitigation.

POLES

The Prospective Outlook on Long-term Energy Systems (POLES) model is a global sectoral model of the world energy system. It has been developed in the framework of a hierarchical structure of interconnected sub-models at the international, regional and national levels. This partial-equilibrium model is solved year-by-year through recursive simulation. It makes provision for international energy prices that are endogenous and for lagged adjustments of supply and demand by world region. The model provides comprehensive energy balances for 47 countries and regions, among them the members of the OECD and key developing countries. Many parts of the global energy system are detailed in POLES, from the primary energy supply sector (oil and gas discovery module) to fairly detailed demand modules (industry, transport, services and dwellings).

- Projections of energy demand and supply by region/country and international oil/gas/coal prices
- Simulation of technology development for electricity supply
- Simulation of CO_2 emissions and analysis of CO_2 abatement policies and carbon values

Articles presenting the POLES model

European Commission (1996). POLES 2.2. European Commission DG XII. EUR 17358 EN.

Criqui, P. Russ, P., Deybe, D. (2006): Impacts of Multi-gas Strategies for Greenhouse Gas Emission Abatement: Insights form a Partial Equilibrium Model, in De la Chesnaye, F.; Wyant, J (eds). P. 251

More information

- POLES : Prospective Outlook on Long-term Energy Systems (http://www.enerdata.net/enerdatauk/solutions/energy-models/poles-model.php)

PRIMES

PRIMES is a modelling system that simulates a market equilibrium solution for energy supply and demand for Europe, covering in total 35 European countries. The model determines the equilibrium by finding the prices of each energy form such that the quantity producers find best to supply match the quantity consumers wish to use. PRIMES takes fossil fuel prices from world energy modeling handled either by POLES model or the Prometheus model. The equilibrium is static (within each time period) but repeated in a time-forward path, under dynamic relationships. The model is behavioural but also represent in an explicit and detailed way the available energy demand and supply technologies and pollution abatement technologies. The system reflects considerations about market economics, industry structure, energy/environmental policies and regulation. These are conceived so as to influence market behaviour of energy system agents. The model explicitly considers the existing stock of equipment, its normal decommissioning and the possibility for premature replacement. At any given point in time, the consumers or producer selects the technology of the energy equipment on an economic basis and can be influenced by policy (taxes, subsidies, regulation) market conditions (tariffs etc.) and technology changes (including endogenous learning and progressive maturity on new technologies).

The electricity module covers the whole Europe, while representing chronological load curves and dispatching at the national level. It contains 26 fuel types and the industrial sector consists of nine sectors. Sectoral value added derived using GEM-E3, transformed in physical output indicators for certain heavy industries. Short term GDP trends are taken from published forecasts (e.g. DG ECFIN). Long term demographic and growth trends are taken from published studies, as for example the DG ECFIN 2009 Ageing Report.

The tertiary sector comprises of 4 sectors. The residential sector distinguishes five categories of dwelling. The transport sector distinguishes passenger transport and goods transport as separate sectors. They are further subdivided in sub-sectors according to the transport mean (road, air, etc.). At the level of the sub-sectors, the model structure defines several technology types (car technology types, for example). The transport sector model is designed to take as inputs results from transport flow models, such as SCENES and TRANSTOOLS.

It covers a medium to long-term horizon (2050). PRIMES currently is the main supplier of DG TREN as it has been used to develop the scenarios and forecasts that are included in the series of publications of DG TREN. The whole model runs with GAMS on a set of 48 parallel processors; input and outputs are organised and stored in Excel files; the full trade electricity model takes 7-8 hours for a run. Similar models as PRIMES have been developed in the USA, including PIES, IFFS and the NEMS model which is currently used by DOE/EIA.

Articles presenting the PRIMES model

P. Capros, The PRIMES Energy System Model: Summary Description; Athens, NTUA**,**
http://www.e3mlab.ntua.gr/manuals/PRIMsd.pdf

PRIMES model e3mlab of iccs/ntua version used for the 2010 scenarios for the european commission including new sub-models:
http://www.e3mlab.ntua.gr/e3mlab/PRIMES%20Manual/The_PRIMES_MODEL_2010.pdf

P. Capros, 2010, The new PRIMES biomass supply model description of version 3.1, Athens, NTUA

More information

- The PRIMES Model (http://www.e3mlab.ntua.gr/e3mlab/index.php?option=com_content&view=category&id=35:primes&Itemid=80&layout=default&lang=en)

GAINS

The Greenhouse gas and Air pollution Interactions and Synergies (GAINS) model brings together information on future economic, energy and agricultural development, emission control potentials and costs, atmospheric dispersion and environmental sensitivities toward air pollution. The model addresses threats to human health posed by fine particulates and ground-level ozone, risk of ecosystems damage from acidification, excess nitrogen deposition (eutrophication) and exposure to elevated levels of ozone, as well as long-term radiative forcing. GAINS calculates impacts for environment (critical loads) and human health (fine particulates and ozone) for 43 European countries and four sea areas, describing their impacts for the European territory with a 50 km grid resolution. GAINS estimates emission control costs from the perspective of a social planner, with a focus on resource costs of emission controls to societies. While this perspective is different from that of private profit oriented actors, it is the appropriate approach for decisions on the optimal allocation of societal resources.

Articles presenting the GAINS model

Amann M, Bertok I, Borken-Kleefeld J, Cofala J, Heyes C, Höglund-Isaksson L, Klimont Z, Nguyen B, Posch M, Rafaj P, Sandler R, Schöpp W, Wagner F, Winiwarter W. (2011) Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications Environmental Modelling & Software, 26(12):1489-1501 (December 2011) (Published online 15 September 2011) http://doi:10.1016/j.envsoft.2011.07.012

Wagner F, Heyes C, Klimont Z, Schoepp W (2013). The GAINS optimzation module: Identifying costeffective measures for improving air quality and short-term climate forcing. IIASA, Laxenburg, Austria. http://www.iiasa.ac.at/publication/more_IR-13-001.php

More information

- The Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS)-Model (http://gains.iiasa.ac.at/models/)

GEM-E3

The GEM-E3 simultaneously representing world regions or EU countries, linked through endogenous bilateral trade. It aims at covering the interactions between the economy, the energy system and the environment, and is based on the GTAP database. The model computes simultaneously the competitive market equilibrium under Walras' law and the optimum balance for energy demand/supply and emission/abatement. GEM-E3 is a dynamic, recursive over time, model, involving dynamics of capital accumulation and technology progress, stock and flow relationships and backward looking expectations. The results of GEM-E3 include projections of full Input-Output tables by country, national accounts, employment, capital, financial flows, balance of payments, public finance and revenues, household consumption and welfare, energy use and supply, and atmospheric emissions. The computation of equilibrium is simultaneous for all domestic markets and their interaction through flexible bilateral trade flows. It has the following characteristics:

- it considers explicitly market clearing mechanisms, and related price formation, in the economy, energy, environment economy markets; prices are computed by the model as a result of supply and demand interactions in the markets, in which economic agents are price takers; through its flexible formulation, it also enables the representation of hybrid or regulated situations, as well as perfect competition.
- it formulates separately the supply or demand behaviour of the economic agents in the individual optimisation of their objectives, and makes them compete within markets cleared by prices that achieve global equilibrium.
- it includes all simultaneously clearing inter-related markets, and represents the system at the appropriate coverage level, with respect to geography, the sub-system (energy, environment, economy) and the dynamic mechanisms of agents' behaviour, including expectations;
- Although it is global, the model exhibits a sufficient degree of disaggregation concerning sectors, structural features of energy/environment and policy-oriented instruments (e.g. taxation). The model formulates production technologies in an endogenous manner allowing for price-driven derivation of intermediate consumption and the demand for services from capital and labour. For the demand side. the model formulates consumer behaviour based on a nested Stone Geary utility function. It distinguishes between durable (equipment) and consumable goods and services. The model is dynamic, driven by the accumulation of capital and equipment. Technological progress is explicitly represented in the production functions and for each production factor.
- The model results from a collaborative efforts by a consortium, involving the National Technical University of Athens (NTUA), the Centre for Economic Studies of the Katholieke Universiteit Leuven and the Centre for European Research (ZEW) as the core modelling team. Other participants in current projects for a further developing of the model are ERASME (Ecole Centrale de Paris), MERIT (University of Maastricht), the Paul Scherrer Institute (PSI) and the University of Budapest of Economic Science. It is an empirical, large-scale model, written entirely in structural form.

Articles presenting the GEM-E3 model

Capros, P., Georgakopoulos, P. , Van Regemorter, D., Proost, S., Schmidt, T.F.N., Koschel, H., Conrad, K., and Vouyoukas, E.L. (1999), Climate Technologies Strategies 2, The Macroeconomic Cost and Benefit of Reducing Greenhouse Gas Emissions in the European Union, ZEW Economic Studies 4 (ZEW, Mannheim)

Mayeres, I., and Van Regemorter, D. (1999), The introduction of the External Effects of Air Pollution in AGE models: Towards the Endogenous Determination of Damage Valuation and its Application to GEM-E3, in the Final report of the GEM-E3 Elite Project of the EU Joule Research Programme

Capros, P., Georgakopoulos, P., Van Regemorter, D., Proost, S., Schmidt, T.F.N., and Conrad, K. (1997), European Union: the GEM-E3 General Equilibrium Model, Economic and Financial Modelling, special double issue, Summer/Autumn

Mayeres and D. Van Regemorter (2003); Modelling the health related benefits of environmental policies - a CGE analysis for the EU countries with GEM-E3, katholieke Universiteit leuven working paper series n°2003-10

More information

- General Equilibrium Model for Economy - Energy – Environment (https://ec.europa.eu/jrc/en/gem-e3)

TM5

The TM5 model is a 3D atmospheric chemistry-transport ZOOM model. It allows the definition of arbitrary zoom regions, which are 2-way nested into the global model. Thus simulations at relatively high spatial resolution (currently 1x1 degrees longitude-latitude) can be performed over selected regions, with boundary conditions always provided consistently from the global model. The definition of vertical layers is linked to the 60 vertical layers of the ECMWF model. The tropospheric TM5 version uses a subset of 25 layers (mostly in the troposphere). Since January 2006, the ECMWF model uses 91 vertical layers, and a 34-layer subset has been created for TM5. Currently, a stratospheric-tropospheric version of TM5 is under development. It is designed to simulate chemical processes which occur from the ground upto 0.1 hPa. This version of TM5 will be coupled to a GCM allowing studies of chemistry-climate interactions to be performed.

Finally, a high-resolution version is being developed. It allows zooming to a spatial resolution of 0.5x0.25 degrees.

Articles presenting the TM5 model

Huijnen, V., Williams, J., van Weele, M., van Noije, T., Krol, M., Dentener, F., Segers, A., Houweling, S., Peters, W., de Laat, J., Boersma, F., Bergamaschi, P., van Velthoven, P., Le Sager, P., Eskes, H., Alkemade, F., Scheele, R., Nédélec, P., and Pätz, H.-W. (2010b). The global chemistry transport model TM5: description and evaluation of the tropospheric chemistry version 3.0. Geoscientific Model Development, 3(2):445-473.
http://www.geosci-model-dev.net/3/445/2010/gmd-3-445-2010.html

Krol, M., Houweling, S., Bregman, B., van den Broek, M., Segers, A., van Velthoven, P., Peters, W., Dentener, F., and Bergamaschi, P. (2005). The two-way nested global chemistry-transport zoom model TM5: algorithm and applications. Atmos. Chem. Phys., 5(2):417-432.
http://www.atmos-chem-phys.net/5/417/2005/acp-5-417-2005.html

More information

- TM5 model – Overview (https://www.projects.science.uu.nl/tm5/TM5_overview.html) (http://tm5.sourceforge.net/)

EMEP

The chemical transport models developed at Meteorological Synthesizing Centre - West (MSC-W) are concerned with the regional atmospheric dispersion and deposition of acidifying and eutrophying compounds (S, N), ground level ozone (O3) and particulate matter (PM2.5, PM10). The Meteorological Synthesizing Centre – West (MSC-W) of EMEP has been performing model calculations in support of UNECE for more than 30 yr and, nowadays also for the European Commission. The MSC-W models have been increasing in complexity and capabilities over this time-period.

Until 1998, 2-D Lagrangian Acid Deposition model was routinely used at EMEP/MSC-W. In 1997 results from the EMEP Eulerian photooxidant model were presented for the first time. In 1999 3-D Eulerian Acid Deposition Model was applied to calculate air concentration and deposition fields for major acidifying and eutrophying pollutants as well as their long-range transport and fluxes across national boundaries. Finally in 2002, the Unified EMEP model, was introduced; A modelling system that unified the acidifying and the oxidant versions of the eulerian model. The Unified EMEP model code (version rv3) was released as open source under the GPL license v3 in February 2008. The release of the code included also a full input data set for 2005 and model results for comparison. The latest EMEP/MSC-W model v.2011-06 open source code with a full input data set for 2008 and model results for comparison has been available since July 2011.

The EMEP Lagrangian model was not explicitly designed to model particulate matter, but it calculated air concentrations of four secondary particles: sulphate, nitrate, ammonium sulphate and ammonium nitrate.

During the development of the models the grid resolution has changed and the description of the EMEP grid both for Lagrangian model (150x150 km2) and the Eulerian model (50x50 km2) can be found. EMEP uses the RAINS (Regional Air Pollution Information and Simulation) model for integrated assessment developed and maintained at the Center for Integrated Assessment Modelling (CIAM).

The model code itself is available at http://www.emep.int, along with the datasets required to run for a full year over Europe.

Articles presenting the EMEP model

Simpson et al. (2012); D. Simpson, A. Benedictow, H. Berge, R. Bergstrom, L. D. Emberson, H. Fagerli, G. D. Hayman, M. Gauss, J. E. Jonson, M. E. Jenkin, A. Nyıri, C. Richter, V. S. Semeena, S. Tsyro, J.-P. Tuovinen, A´ . Valdebenito, and P. Wind; The EMEP MSC-W chemical transport model – Part 1: Model description; Atmos. Chem. Phys. Discuss., 12, 3781–3874, 2012 http://www.atmos-chem-phys-discuss.net/12/3781/2012/

More information

- Convention on Long-range Transboudary Air Pollution (http://www.emep.int/index_model.html)

CHIMERE

The CHIMERE multi-scale model is primarily designed to produce daily forecasts of ozone, aerosols and other pollutants and make long-term simulations (entire seasons or years) for emission control scenarios. CHIMERE runs over a range of spatial scale from the regional scale (several thousand kilometers) to the urban scale (100-200 Km) with resolutions from 1-2 Km to 100 Km. CHIMERE proposes many different options for simulations which make it also a powerful research tool for testing parameterizations, hypotheses. I has also been thoroughly validated against measurement and other tools and is now been extensively used to support policy. CHIMERE is a parallel model that has been tested on machines ranging from desktop PCs running the GNU/Linux operating system, to massively parallel supercomputers.

Articles presenting the CHIMERE model

Menut L, B.Bessagnet, D.Khvorostyanov, M.Beekmann, N.Blond, A.Colette, I.Coll, G.Curci, G.Foret, A.Hodzic, S.Mailler, F.Meleux, J.L.Monge, I.Pison, G.Siour, S.Turquety, M.Valari, R.Vautard and M.G.Vivanco, 2013, CHIMERE 2013: a model for regional atmospheric composition modelling, Geoscientific Model Development, 6, 981-1028, doi:10.5194/gmd-6-981-2013

More information

- The Chimere chemistry-transport model (http://www.lmd.polytechnique.fr/chimere/)

CAPRI

CAPRI is a partial equilibrium model for the agricultural sector developed for policy impact assessment of the Common Agricultural Policy and trade policies from global to regional scale with a focus on the EU.

Supply module: separate, regional, non-linear programming models allowing to directly implement most policy measures with highly differentiated set of activities. Allocation based on profit maximising behaviour calibrated to exogeneous elasticities (animals) and estimated multi-product cost functions (annual crops); provision of nutrient balances and gas emissions with global warming potential based on production system. Template approach with structurally identical models which differ in parametrization. Cover completely EU agriculture (280 regional models or 1.900 farm type models)

Market module: global spatial multi-commodity Model. 28 trade blocks and 60 countries. Flexible and well-behaved functional forms. Armington assumption to model bi-lateral trade flows. Tariff Rate Quotas and preferential agreements. Subsidised exports and market interventions.

Spatial downscaling of crop shares, yields, stocking densities, fertilizer application rates to 150.000 Homogenous Soil Mapping Units (cluster of 1x1 km grid cells) for EU27 and link to bio-physical model DNDC.

Technically, CAPRI is realised in GAMS and steered by a Graphical User Interface realised in Java. The GAMS code and the data base are hosted on SVN version control server.

Articles presenting the CAPRI model

Britz., W., Witzke, P., CAPRI model documentation 2014. http://www.capri-model.org/docs/capri_documentation.pdf

More information

- Common Agricultural Policy Regionalised Impact Modelling System (http://www.capri-model.org/dokuwiki/doku.php?id=start)

TREMOVE

TREMOVE is a policy assessment model to study the effects of different transport and environment policies on the emissions of the transport sector. The model estimates the transport demand, modal shifts, vehicle stock renewal and scrappage decisions as well as the emissions of air pollutants and the welfare level, for policies as road pricing, public transport pricing, emission standards, subsidies for cleaner cars etc. The model covers passenger and freight transport in 31 countries and covers the period 1995-2030.

Articles presenting the TREMOVE model

Van Herbruggen., Bart., TREMOVE 2.7 User Manual
Transport & Mobility Leuven, 2007,
http://www.tmleuven.com/methode/tremove/TREMOVE_v2.7_User_Manual.pdf,

More information

- TREMOVE economic transport and emissions model (http://www.tmleuven.com/methode/tremove/home.htm)

ENV-Linkages

The OECD ENV-Linkages General Equilibrium (GE) model is the successor to the OECD GREEN model for environmental studies The ENV-Linkages model is a recursive dynamic neo-classical general equilibrium model. In its current form, the model represents the world economy in 15 countries/regions, each with 26 economic sectors, including seven different technologies to produce electricity. The core of the static equilibrium is formed by the set of Social Account Matrices (SAMs) that described how economic sectors are linked; these are based on the GTAP database (GTAP, 2008; version 7.1). All production in ENV-Linkages is assumed to operate under cost minimisation with an assumption of perfect markets and constant return to scale technology. The production technology is specified as nested CES production functions in a branching hierarchy. International trade is based on a set of regional bilateral flows. The model adopts the Armington specification, assuming that domestic and imported products are not perfectly substitutable. The ENV-Linkages model has a simple recursive-dynamic structure, where households base their decisions on static expectations concerning prices and quantities. Household consumption, demand and savings are implemented through an "Extended Linear Expenditure System". The land-based sectors, including 3 agricultural sectors and forestry, provide direct links to indicators for climate change (e.g. emissions from deforestation), biodiversity (e.g. land under forest cover) and water. The land use module of the ENV-Linkages model is based on information provided by PBL and LEI and calibrated to mimic land use relations in the IMAGE suite of models (Kram et al., 2012). the ENV-Linkages represents the land-data in a stylised and aggregated manner where sector-specific transformation elasticities are used to represent land use changes. The model calculates up to 2050.

Articles presenting the ENV-Linkages model

Duval, R. and C. de la Maisonneuve (2009), Long-Run GDP Growth Scenarios for the World Economy, OECD Economics Department Working Paper 663, February 2009. http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?doclanguage=en&cote=eco/wkp(2009)4http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?doclanguage=en&cote=eco/wkp(2009)4

Chateau, J., R. Dellink, E. Lanzi and B. Magne (2012), "An overview of the ENV-Linkages model – version 3", OECD Environment Working Paper. http://www.oecd-ilibrary.org/environment-and-sustainable-development/an-overview-of-the-oecd-env-linkages-model_5jz2qck2b2vd-en

Burniaux, J. and J. Chateau (2008), "An Overview of the OECD ENV-Linkages Model", OECD Economics Department Working Papers, No. 653, OECD Publishing. http://dx.doi.org/10.1787/230123880460

Chateau, J., C. Rebolledo and R. Dellink (2011), "An Economic Projection to 2050: The OECD "ENV-Linkages" Model Baseline", OECD Environment Working Papers, No. 41, OECD Publishing. http://dx.doi.org/10.1787/5kg0ndkjvfhf-en

More information

- An Overview of the OECD ENV-Linkages Model (http://www.oecd-ilibrary.org/environment-and-sustainable-development/an-overview-of-the-oecd-env-linkages-model_5jz2qck2b2vd-en)
- Environmental indicators, modelling and outlooks Environmental-Economic Modelling (http://www.oecd.org/env/indicators-modelling-outlooks/modelling.htm)

FASST

In order to evaluate in a swift and integrated way impacts of air pollutant emission scenarios on a global scale, the fast scenario screening tool TM5-FASST was developed at JRC-H02. TM5-FASST is a global air quality source-receptor model, derived as a linearized version from the full chemical transport model TM5-CTM. The model takes as input pollutants emissions from 56 source regions with global coverage, and calculates resulting pollutant concentrations and their associated impacts on human health and ecosystems. Besides it also provides climate metrics such as CO2eq of emitted short lived climate pollutants. TM5-FASST is currently applied in the framework of the FP7 LIMITS project to assess the co-benefits of combined climate and air pollution strategies in long-term climate mitigation scenarios. Five different integrated assessment models delivered a set of air pollutant emission scenarios consistent with the underlying energy and climate scenarios, which were used as input for the TM5-FASST model to determine the impacts on human health, vegetation and radiative forcing. The results show that stringent climate policies provide a significant air quality benefit compared to current legislation air quality policy, both in terms of reduced premature mortalities and improved crop yields.

More information

- European Commission, Joint Research Centre. FASST. A Fat Scenario Screening Tool for global air quality and instantaneous radiative forcing.
  http://ccaqu.jrc.ec.europa.eu/seminars/FASST_presentation_unit.pdf

ECHAM5-MESSy

The ECHAM/MESSy Atmospheric Chemistry (EMAC) model is a numerical chemistry and climate simulation system that includes sub-models describing tropospheric and middle atmosphere processes and their interaction with oceans, land and human influences. It uses the Modular Earth Submodel System (MESSy) to link multiinstitutional computer codes. The core atmospheric model is the 5th generation European Centre Hamburg general circulation model (ECHAM5). The model has been shown to consistently simulate key atmospheric tracers such as ozone, water vapour and lower and middle stratospheric NOy.

Articles presenting the ECHAM5-MESSy model

Jockel, P., Tost, H., Pozzer, A., Br ¨ uhl, C., Buchholz, J., Ganzeveld, L., Hoor, P., Kerkweg, A., Lawrence, M. G., Sander, R., Steil, B., Stiller, G., Tanarhte, M., Taraborrelli, D., Aardenne, J. V., and Lelieveld, J.: The atmospheric chemistry general circulation model ECHAM5/MESSy1: consistent simulation of ozone from the surface to the mesosphere, Atmos. Chem. Phys., 6, 5067–5104, 2006, http://www.atmos-chem-phys.net/6/5067/2006

More information

- The highly structured Modular Earth Submodel System (MESSy). (http://www.messy-interface.org/)
- ECHAM, (http://www.mpimet.mpg.de/en/science/models/echam.html)

EC-IMAGES

Exploring linking IMAGE and the complex climate model EC-Earth, in cooperation with Utrecht University and the Dutch Meteorological institute KNMI). Feedbacks between climate and human systems assessed with a coupled Integrated Assessment - Climate Modeling Sytem. Anthropogenic activities have a detectable impact on climate on global and continental scales. Understanding the processes that determine these impacts is of large scientific and societal interest. Models that integrate the state-of-the-art knowledge are used to make projections for future changes. In the past 2 decades, climate models were used to calculate the impacts by prescribing the human impact. Greenhouse gas concentration or emission scenarios from integrated assessment models and land cover changes were used for that purpose. The integrated assessment models contain very simple climate models (global energy balance atmosphere models and upwelling-diffusion ocean), but a sophisticated representation of human activities and related emissions. The opposite is the case for climate models. Physical processes are well described, but the human impact is prescribed by boundary conditions (such as CO2 equivalent concentrations, sometimes emissions, and land cover maps). Here we intend to bridge that gap by exploring explicitly the feedbacks and sensitivities between climate and human activities and vice versa in 2 state-of-the-art modeling systems that will be used for the next IPCC AR5 report: the Integrated Assessment Model IMAGE and the AOGCM EC-Earth.

Articles presenting the EC-IMAGES model

Clifford Chuwah,Twan van Noije Detlef P. van Vuuren, Wilco Hazeleger , Achim Strunk a, Sebastiaan Deetman, Angelica Mendoza Beltran, Jasper van Vliet. Implications of alternative assumptions regarding future air pollution control in scenarios similar to the Representative Concentration Pathways. http://dx.doi.org/10.1016/j.atmosenv.2013.07.008

E3MG

E3MG is a macro-econometric non-equilibrium hybrid simulation model of the global E3 system, estimated on annual data 1971-2002 for 20 world regions. It is used for annual projections to 2030 and in 10-year intervals thereafter to 2100. E3MG is based upon a New Economics view of long-term dynamics (Barker, 2008), drawing as well on Post Keynesian features taking a historical approach of cumulative causation and demand-led growth, and incorporating technological progress in gross investment enhanced by research and development (R&D) expenditures. It is a non-equilibrium model implying that labor, foreign exchange and financial markets do not necessarily clear but have deficits or surpluses in open economies depending on the year and region. A bottom-up energy-technology simulation has been incorporated allowing for the explicit modeling of 28 energy technologies. This allows for the modelling of a two-way feedback between the economy, energy demand/supply and anthropogenic emissions. One of the model's limitations is that parameters estimated from a recent time series of 32-years may not be time invariant over coming decades.

Articles presenting the E3MG model

Terry Barkera, Annela Angera, Unnada Chewpreechab, Hector Pollittb ;A new economics approach to modelling policies to achieve global 2020 targets for climate stabilisation; International Review of Applied Economics Volume 26, Issue 2, 2012; pages 205-221

More information

- The E3MG Model (http://www.camecon.com/EnergyEnvironment/EnergyEnvironmentGlobal/ModellingCapability/E3MG.aspx)

WITCH

The WITCH (World Induced Technical Change Hybrid) model is designed to assist in the study of the socio-economic dimension of climate change. The model has been developed with the aim of studying mitigation and adaptation policies for climate change control.

WITCH is a Regional Integrated Assessment Hard-Link Hybrid Model. Its top-down component consists of an intertemporal optimal growth model in which the energy input of the aggregate production function has been expanded to give a bottom-up like description of the energy sector. World countries are grouped in twelve regions that strategically interact following a game theoretic structure. A climate module and a damage function provide the feedback on the economy of carbon dioxide emissions into the atmosphere.

The model is structured so as to provide normative information on the optimal responses of world economies to climate damages and to model the channels of transmission of climate policy to the economic system. The dynamic and strategic features of the model, the energy sector specification and the technical change options make WITCH an especially suited tool to explicitly analyze the climate change issue, marked by medium term investment choices and long term economic dynamics and environmental responses.

Articles presenting the WITCH model

Bosetti, V, Massetti, E, Tavoni, M. The WITCH model: structure, baseline, solutions. FEEM Working paper N.10 2007. http://ageconsearch.umn.edu/bitstream/12064/1/wp070010.pdf

Bosetti, V, Carraro, C, Galeotti, M, Massetti, E, Tavoni, M. WITCH: a world induced technical change hybrid model. Energy J, Special Issue "Hybrid Modelling of Energy Environment Policies: Reconciling Bottom-up and Top-down"; 2006, 13–38.

Bosetti, V, Carraro, C, Tavoni, M. Timing of mitigation and technology availability in achieving a low-carbon world. Environ Resour Econ 2012, 51:353–369.

More information

- WITCH (World Induced Technical Change Hybrid model) (http://www.witchmodel.org)

GCAM/-IIM (PNNNL-JGCRI, USA/IIM, India)

The Global Change Assessment Model (GCAM) is a global integrated assessment model with particular emphasis on the representation of human earth systems including interactions between the global economic, energy, agricultural, land use and technology systems. Previously known as MiniCAM. The GCAM physical atmosphere and climate are represented by the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC).The current version of the model is GCAM 3.1.GCAM is freely available as a community model. Sixteen emissions tracked including CO_2, CH_4, N_2O, and SO_2. 5-year time step. Run period 1990 – 2095.

Energy Sector Detail: Three end-use sectors (Buildings, Industry, Transportation). Energy supply and transformation sectors: fossil-fuels (oil, natural gas, coal), biomass (traditional & modern), electricity, hydrogen, synthetic fuels.

Regional Detail: Global coverage with 14 regions (United States, Canada, Western Europe, Japan, Australia & New Zealand, Former Soviet Union, Eastern Europe, Latin America, Africa, Middle East, China [& Asian Reforming Economies], India, South Korea, Rest of South & East Asia).

The agriculture-land-use model (AgLU) endogenously determines land use, land cover, and the stocks and flows of carbon from terrestrial reservoirs. AgLU is fully integrated with the GCAM energy and economy modules. In GCAM 3.0, the model data for the agriculture and land use parts of the model is comprised of 151 subregions in terms of land use, based on a division of the extant agro-ecological zones (AEZs) within each of GCAM's 14 global geo-political regions. Within each of these 151 subregions, land is categorized into approximately a dozen types based on cover and use. Production of approximately twenty crops is currently modeled, with yields of each specific to each of the 151 subregions. The model is designed to allow specification of different options for future crop management for each crop in each subregion. Stocks and flows of terrestrial carbon and other greenhouse gases are determined by associated land use and land cover and land-use-land-cover changes.

Articles presenting the GCAM/-IIM model

Global Change Assessment Model Description. Available at:
http://www.globalchange.umd.edu/models/gcam

Brenkert A, S Smith, S Kim, and H Pitcher. 2003. Model Documentation for the MiniCAM. PNNL-14337, Pacific Northwest National Laboratory, Richland, Washington. Available at:
http://www.globalchange.umd.edu/models/MiniCAM.pdf

Kim, S.H., J. Edmonds, J. Lurz, S. J. Smith, and M. Wise (2006) "The ObjECTS Framework for Integrated Assessment: Hybrid Modeling of Transportation " Energy Journal (Special Issue #2) pp 51-80.

More information

- GCAM community.
  (http://www.globalchange.umd.edu/models/gcam/gcam-community/)

IMAGE/TIMER/FAIR

http://www.pbl.nl/image

IMAGE

The Integrated Model to Assess the Global Environment (IMAGE) has initially been developed as an integrated assessment model to study anthropocentric climate change (Rotmans, 1990). Later it was extended to include a more comprehensive coverage of global change issues in an environmental perspective (Alcamo et al. 1994, IMAGE team, 2001). The current main objectives of IMAGE are to contribute to scientific understanding and support decision-making by quantifying the relative importance of major processes and interactions in the society-biosphere-climate system (see further: http://www.pbl.nl/image). IMAGE provides a dynamic and long-term assessment of the systemic consequences of global change up to 2100. The model was set up to give insight into causes and consequences of global change up to 2100 as a quantitative basis for analysing the relative effectiveness of various policy options for addressing global change. In earlier studies two models associated with, but not integrated in IMAGE, were used to provide basic drivers for the IMAGE model. These are the general equilibrium economy model, WorldScan (CPB, 1999), and the population model, PHOENIX (Hilderink, 2000). The WorldScan model provides input for IMAGE on economic developments, and PHOENIX provides input on demographic developments for both IMAGE and WorldScan.

TIMER

Within the Integrated Model to Assess the Global Environment (IMAGE), the global energy system model ***TIMER*** provides regional energy consumption, energy efficiency improvements, fuel substitution, supply and trade of fossil fuels and renewable energy technologies. On the basis of energy use and industrial production TIMER computes emissions of greenhouse gases (GHG), ozone precursors and acidifying compounds.

TIMER describes the investment in, and the use of, different types of energy options within a simulation framework. The value of these options is affected by technology development (learning-bydoing) and resource depletion. The TIMER model describes long-term trends in the world energy system. It encompasses long-term energy demand, resource

depletion and technology development affecting various energy sources, cost based substitution in production, and the development of climate policy. The substitution across different energy carriers is described on the basis of multinomial logit equations. IMAGE computes land-use changes and emissions from land use, natural ecosystems and agricultural production systems. The model also takes account of the exchange of carbon dioxide between terrestrial ecosystems and the atmosphere. The IMAGE model is particularly strong in the detailed description of energy technologies and of geographically explicit land use. The integration of land and energy use in one model is itself noteworthy. A drawback of the model

is that economic development is treated as an exogenous driver. Hence changes in the energy sector and in land use are decoupled from changes in GDP.

FAIR

The policy decision-support tool 'Framework to Assess International Regimes for the differentiation of commitments' (FAIR) has been developed to explore and evaluate the environmental and abatement cost implications of various international regimes for differentiation of future commitments for meeting long-term climate targets, such as stabilization of the atmospheric greenhouse gas concentrations (den Elzen, 2005). The model aims to support policy makers by quantitatively evaluating the environmental and costs implications of a range of approaches and linking these to targets for global climate protection. The model was also used to support dialogues between scientists, NGOs and policy makers. To this end the model is set up as an interactive tool with a graphical user interface, allowing for interactive changing and viewing model input and output. The FAIR model consists of three linked models, including a climate model, an emission allocation model and an abatement costs model. The climate model calculates the climate impacts of global emission profiles and emission scenarios, and determines the global emission reduction objective based on the difference between the global emissions scenario (without climate policy) and a global emission profile (including climate policy). The emission allocation model calculates the regional greenhouse gas (GHG) emission allowances for different regimes for the differentiation of future commitments within the context of the global reduction objective from the climate model. The abatement costs model calculates the regional abatement costs and emission levels after trading on the basis of the emission allowances coming from the emission allocation model following a least-cost approach. The model makes full use of the flexible Kyoto mechanisms as emissions trading and substitution of reductions between the different gases and sources. Various data sets of historical emissions, baseline scenarios, emission profiles and marginal abatement cost (MAC) curves are included in the model framework to assess the sensitivity of the outcomes to variation in these key inputs.

<u>Articles presenting the FAIR model</u>

PBL (2014), Integrated Assessment of Global Environmental Change with IMAGE 3.0 - Model description and policy applications, Elke Stehfest, Detlef van Vuuren, Tom Kram, Lex Bouwman, Rob Alkemade, Michel Bakkenes, Hester Biemans, Arno Bouwman, Michel den Elzen, Jan Janse, Paul Lucas, Jelle van Minnen, Mike Muller, Anne Gerdien Prins, Netherlands Environmental Assessment Agency, The Hague, The Netherlands. http://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0

Schaeffer, M. and E. Stehfest (2010). *The climate subsystem in IMAGE updated to MAGICC 6.0*, PBL report 500110005, PBL Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands.

de Vries B; Vuuren D van ; Elzen M den ; Janssen M (2001), The Timer IMage Energy Regional (TIMER) Model, Report no. 461502024, National Institute for Public Health and the Environment (RIVM), Bilthoven.

den Elzen and Paul L. Lucas (2005), The FAIR model: A tool to analyse environmental and costs implications of regimes of future commitments. *Environmental Modeling and Assessment*, 10 (2): 115-134, doi: http://dx.doi.org/10.1007/s10666-005-4647-z.

<u>More information</u>

- IMAGE Integrated Model to Assess the Global Environment (http://themasites.pbl.nl/models/image/index.php/Main_Page)

MERGE-AIR/MERGE

Key features include a nine-region global disaggregation, a combined ‘top-down’ Ramsey type economic and ‘bottom-up’ engineering modeling approach, a simple climate model, and international trade. Regional technological learning with global spillovers and costly climate-change impacts enhance the regional links and. Technologies for electricity generation (including options for CCS), and secondary fuel production (synthetic fuels from coal and biomass, H2 from a range of sources, including options for CCS) are explicitly included in MERGE. Technological learning is represented by two factor learning curves for technology investment costs. A limitation in MERGE is that the model relies on perfect competition and information, production/utility function continuity, representative agents, etc. The low level of technology detail also permits only a generic representation of end-use energy efficiency as explicit end-use technologies are not represented.

Articles presenting the MERGE-AIR model

Alan S. Manne, Richard G. Richels MERGE: An Integrated Assessment Model for Global Climate Change, Stanford University, EPRI. http://web.stanford.edu/group/MERGE/GERAD1.pdf

More information

- MERGE, A Model for Evaluating the Regional and Global Effects of GHG Reduction Policies (http://web.stanford.edu/group/MERGE/)

WORLDSCAN

WorldScan is a recursively dynamic general equilibrium model for the world economy, based on GTAP database. WorldScan has been developed to construct long-term scenarios for the global economy and to enable policy analyses in the field of international economics. WorldScan can be adapted to arbitrary sector and country Classifications. WorldScan divides the world into twelve regions.

Articles presenting the WORLDSCAN model

CPB (1999), Worldscan: the Core Version, CPB Netherlands Bureau for Economic Policy Analysis, The Hague, the Netherlands. http://www.cpb.nl/publicatie/worldscan-de-basisversie

More information

- Worldscan; a model for international economic policy analysis (http://www.cpb.nl/en/publication/worldscan-model-international-economic-policy-analysis)

GTAP

The standard GTAP Model is a multiregion, multisector, computable general equilibrium model, with perfect competition and constant returns to scale. Innovative aspects of this model include:

- The treatment of private household preferences using the non-homothetic CDE functional form.
- The explicit treatment of international trade and transport margins. Bilateral trade is handled via the Armington assumption.
- A global banking sector which intermediates between global savings and consumption.

The GTAP Model also gives users a wide range of closure options, including unemployment, tax revenue replacement and fixed trade balance closures, and a selection of partial equilibrium closures (which facilitate comparison of results to studies based on partial equilibrium assumptions).

Articles presenting GTAP the model:

Lejour et al., 2006

GTAP (2008), Global Trade, Assistance, and Production : The GTAP 7 Data Base, Narayanan, B. and Walmsey, T. Editors, Center for Gloabal Trade Analysis, Dpt of Agriculutural Economics, Purdue University. https://www.gtap.agecon.purdue.edu/resources/working_papers.asp

More information

- Global Trade Analysis Project (https://www.gtap.agecon.purdue.edu/models/current.asp)

MAGNET

MAGNET is a general equilibrium model of the world economy based on the Global Trade Analysis Project (GTAP) model, focusing on the agricultural sector and the associated land use.

The model counts such options by production and consumption of proteins in order to greenhouse gas emissions and loss of biodiversity. Meat, dairy, arable and horticulture are present in the model, but fish is forced outside the analysis. Especially the indirect use of land to feed the fish in aquaculture has great influence on land use. Clients see it as a major shortcoming that fish remains out of the analysis remains.

Articles presenting the MAGNET model

Banse et al., 2008, Banse, M., H. van Meijl, A. Tabeau and G. Woltjer, Will EU Biofuel Policies affect Global Agricultural Markets? European Review of Agricultural Economics, 2008. 35: p. 117-141. https://www.wageningenur.nl/upload_mm/5/6/f/3b7e0f62-97a6-4104-81e9-570c9ea8c1f1_WillEUBiofuelPoliciesaffectGlobalAgriculturalMarke.pdf

Banse, M., H. van Meijl, and G. Woltjer, Consequences of EU Biofuel Policies on Agricultural Production and Land Use. Choices, 2008. 23(3): p. 22-27. http://www.farmdoc.illinois.edu/policy/choices/20083/theme1/2008-3-05.pdf

Eickhout, B., H. , H. van Meijl, A. Tabeau and E. Stehfest , The impact of environmental and climate constraints on global food supply. In: Economic Analysis of Land Use in Global Climate Change Policy, ed. T.W. Hertel, S.Rose, and R. Tol. http://ideas.repec.org/p/gta/workpp/2608.html

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Nowicki, P., H. van Meijl, A. Knierim, M. Banse, J. Helming, O. Margraf, B. Matzdorf. R. Mnatsakanian, M. Reutter, I. Terluin, K. Overmars, D. Verhoog, C. Weeger, H.Westhoek (2006). Scenar 2020 – Scenario study on agriculture and the rural world. Contract No. 30 - CE - 0040087/00-08.European Commission, Directorate-General Agriculture and Rural Development, Brussels. http://ec.europa.eu/agriculture/publi/reports/scenar2020/index_en.htm

More information

- Expansion Magnet (https://www.wageningenur.nl/en/project/Expansion-MAGNET.htm)

COPERT

COPERT 4 is a software tool used world-wide to calculate air pollutant and greenhouse gas emissions from road transport. The development of COPERT is coordinated by the European Environment Agency (EEA), in the framework of the activities of the European Topic Centre for Air Pollution and Climate Change Mitigation. The European Commission's Joint Research Centre manages the scientific development of the model. COPERT has been developed for official road transport emission inventory preparation in EEA member countries. However, it is applicable to all relevant research, scientific and academic applications.

Data from COPERT are included in the GAINS integrated assessment model used by the UNECE LRTAP Convention and the European Commission to identify cost effective pollutant mitigation strategies that take into account synergies and trade-offs between the control of local and regional air pollution and the mitigation of greenhouse gas emissions.

The TREMOVE policy assessment model assesses the effects of different transport and environment policies on transport emissions. The COPERT II emission factors and methodology were implemented in the road transport module of the first TREMOVE version in 1999, updated to COPERT III in 2004 and again to COPERT 4 in 2006.

The integration of EU transport and environment policies is monitored by the Transport and Environment Reporting Mechanism (TERM). COPERT 4 is used to calculate various TERM indicators for road transport.

COPERT, through its links to TREMOVE, has been used in impact assessment studies of the European Commission to evaluate the impact of proposed technological and legislative measures to road transport. Examples include measures to reduce CO2 emissions from passenger cars, the introduction of EURO VI standards for heavy duty vehicles, effects of the internalisation of external costs, and others.

Articles presenting the COPERT model

Dimitrios Gkatzoflias, Chariton Kouridis, Leonidas Ntziachristos
and Zissis Samaras, Computer programme to calculate emissions from road transport, EMISIA, 2012. http://www.emisia.com/sites/default/files/COPERT4v9_manual.pdf

More information

- COPERT website
  (http://www.emisia.com/copert)

EU-FASOM/DNDC

Three major arguments can be made. First, EUFASOM (The European Forest and Agricultural Sector Optimization Model) and its US counterpart are currently the only bottom-up models, which portray the competition between agriculture, forestry, bioenergy, and nature reserves for scarce land at large scales. These models integrate observed variation in land qualities and technologies with environmental impacts and global market feedbacks. This approach enables the quantification of economic potentials for environmental problem mitigation but also the estimation of leakage effects. Leakage of environmental impacts is perhaps the biggest threat to land use policies, yet it is typically ignored in bottom-up. models. EUFASOM goes beyond the majority of existing economic models in portraying the environmental effects of land use. Multiple greenhouse gas and soil state impacts are estimated with detailed environmental process models. The complex dynamic relationship between land management trajectories and soil quality is represented through Markov chains. A parallel to EUFASOM developed European wetland optimization estimates the impacts of land use impacts on conservation of 69 wetland species. Thus, EUFASOM is better equipped than previous models to assess impacts and interdependencies of climate, biodiversity, soil, and food policies.

Although searches through the scientific literature may reveal numerous integrated land use assessments, the number of maintained state-of-the-art models is small. Essentially, many land use models are dissertation products where the requirement of independent work limits the quality of data and model. EUFASOM is part of an integrated assessment framework where a large team of collaborating researchers from different countries and different disciplines synthesize data, models, and expertise. The model is available for other researchers provided that improvements are shared.

Articles presenting the EU-Fasom model

The European Forest and Agricultural Sector Optimization Model – EUFASOM (http://www.uni-hamburg.de/Wiss/FB/15/Sustainability/schneider/florian/eufasom.pdf)

CCE-impacts

- The CCE IMPACTS database is a combination of many very detailed and often complex (bio/geo)chemical and ecological sub-models calculating critical loads and CL exceedance
- The structure of the models incorporates highly detailed representations of processes affecting the soil system and impacts on ecosystems, representing the scientific state-of-the-art and knowledge and understanding of the impacts
- Complexity of processes may not be evident in relation to interpreting the effects of abatement policies

Articles presenting the CCE-impacts model

Jean-Paul Hettelingh, Maximilian Posch, Jaap Slootweg, The CCE-EIA Ecosystems Impact Model. http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=EC4MACS_CCE_Methodologies_Final.pdf

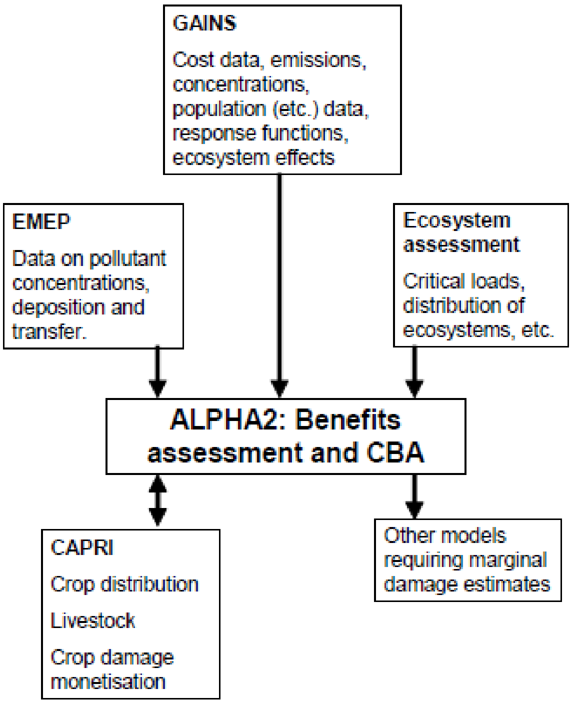
More information

- European Consortium for Modelling of Air Pollution and Climate Strategies. (http://www.ec4macs.eu/)

Alpha-2

The original version of ALPHA (Atmospheric Long-range Pollution Health/environment Assessment Model was developed at AEA Technology in the 1990s, drawing extensively on the ExternE research programme, and was used to inform development of the EC‟s Acidification Strategy, the Ozone Directive, the National Emission Ceilings Directive and the Gothenburg Protocol to the UN/ECE Convention on Long Range Transboundary Air Pollution. ALPHA2 has been developed within Microsoft Access.

The word „benefits‟ is used because most previous applications of the model have considered the benefits of new environmental policy. However, the word is used here in a very broad sense. It applies to both physical or biological benefits such as changes in health impacts (e.g. hospital admissions, reduced longevity) as well as their monetised equivalent. In some cases benefits may be negative (i.e. „costs‟ or „disbenefits‟).



Articles presenting the Alpha-2 model

The ALPHA Benefit Assessment Model

http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=EC4MACS_Alpha_Methodologies_Final.pdf

The ALPHA-2 benefit Assessment Model

http://www.ec4macs.eu/content/report/Uncertainty%20Reports%20of%20Models/ALPHA2_Uncertainty_Report_Final.pdf

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