Temporal and Spatial Distribution of Carbon Emissions from Fossil Fuel Use

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Abstract

This chapter describes the need for and methodologies applied to the distribution of emissions of carbon (mainly carbon dioxide, methane and carbon monoxide) with high temporal and spatial resolution. It briefly addresses aspects of uncertainty assessment and concludes on the requirements for a future development of temporally and spatially detailed datasets on carbon emissions from fossil fuel use.

Introduction

In the early stages of research into climate change, the focus was on the quantification of global and regional carbon cycles. At this stage, the accurate determination of location and time of emissions played a less prominent role. But with the growing need for verification experiments to underpin and support policy development, and thus the application of climate and atmospheric dispersion models, it became evident that both anthropogenic and biogenic carbon emissions had to be provided in a spatial and temporal resolution matching the requirements of said models.

The methodology for the temporal and spatial resolution of anthropogenic emissions in general has been around for some time. Some of the techniques described in the following sections have for instance been developed for the application of atmospheric dispersion models to quantify acid deposition and ambient air concentrations of tropopspheric ozone. One major activity during the 1990s in this field has been the work within the EUROTRAC subproject Generation and Evaluation of Emission Data (GENEMIS), which has been documented in (Friedrich and Reis, 2004).

Carbon Emissions from Fossil Fuel Use

Quantification of anthropogenic carbon emissions

In comparison to for instance emissions of non-methane volatile organic compounds from solvent use, emissions of carbon dioxide and carbon monoxide from the combustion of fossil fuels are less difficult to quantify. On the other hand, methane emissions originate from a portfolio of sources, most of them non-combustion activities, and hence need different approaches for a temporal and spatial distribution.

Carbon dioxide (CO_2)

Complete combustion of fossil fuels releases carbon stored in coal, oil and natural gas into the atmosphere. In combination with oxygen from the air needed for the combustion process, CO_2 is formed and emitted.

Carbon monoxide (CO)

CO is a product of incomplete combustion, when fossil fuels are converted in an atmosphere lacking oxygen necessary for complete combustion. The ratio of CO production varies with the availability of oxygen in the combustion chamber and technologies such as lean engine concepts as well as combustion chamber optimisations can influence the amount of CO formed significantly.

Methane (CH_4)

Methane emissions sources vary with regions, global estimates assuming about one quarter stemming from enteric fermentation in animals, another quarter originating from gas, oil and coal production. Other major sources include municipal waste disposal in landfills and wastewater treatment as well as rice cultivation. These processes are not combustion related and some of them are biogenic/geogenic sources, with significant uncertainties.

Emission factors and activity rates

Common practise for the determination of emission values is the use of emission factors (i.e. the specific amount of a substance emitted per a specific activity unit) and activity rates (for instance the unit of thermal energy converted). While this approach is straightforward, its implications for temporal and spatial distribution of emissions are profound. In most cases, the temporal and spatial patterns, e.g. for the creation of a country emission inventory, are of less importance, hence emission factors and activity rates are used without expressing them as a function of space and time. However, in most cases, activity rates will be dependent on factors such as the time of the year, meteorological parameters, and show distinctive temporal patters (diurnal, weekly, monthly or annual). At the same time, meteorological and behavioural patterns of activity rates may change with locations. The methodologies for the temporal and spatial resolution are described in the next section.

Uncertainties are subject to significant variability due to the large number of influencing factors in the determination of emissions, either as national annual totals, or with high temporal and spatial resolution. Typcially, only rough assessments of uncertainty levels are available (see e.g. *Table x.1* below).

Magnitude of annual emissions in Europe

Emission inventories are compiled for different purposes and in the case of carbon emissions from fossil fuel use, there are three main activities to be mentioned:

- The *Emission Database for Global Atmospheric Research*[1] (EDGAR)
- Data submissions of signatories to the UNFCCC[2]
- Data submissions to the EMEP[3] programme

EDGAR covers the widest range of substances on a global scale, while UNFCCC data are limited to greenhouse gases and EMEP solely collects data relevant under the UNECE Convention on Long-Range Transboundary Air Pollution (CO, but excluding GHGs).

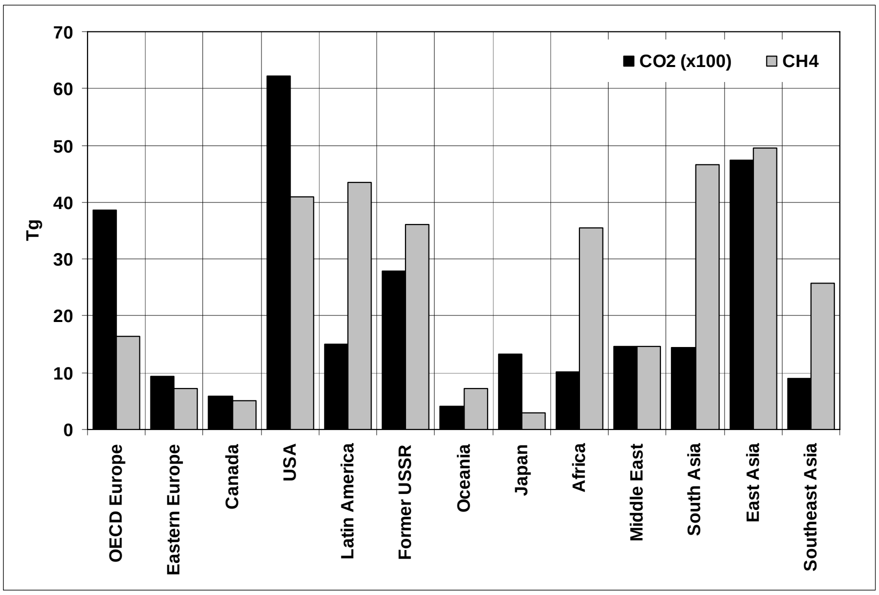

Fig. x.1. CO_2 and CH_4 emissions for the year 2000 in the EDGAR database (Source: EDGAR 32FT2000)

Fig. x.1 displays emissions of CO_2 and CH_4 for different world regions, showing a large variation of relative contributions to the global total emissions. In a similar way, Fig. x.2 indicates emissions as reported under the UNFCCC, with some slight differences in overall emission levels, which most likely originate from different emission sources being excluded from

[1] http://www.mnp.nl/edgar/
[2] http://unfccc.int
[3] http://webdab.emep.int/

the framework convention, which are comprised in the EDGAR inventory figures.

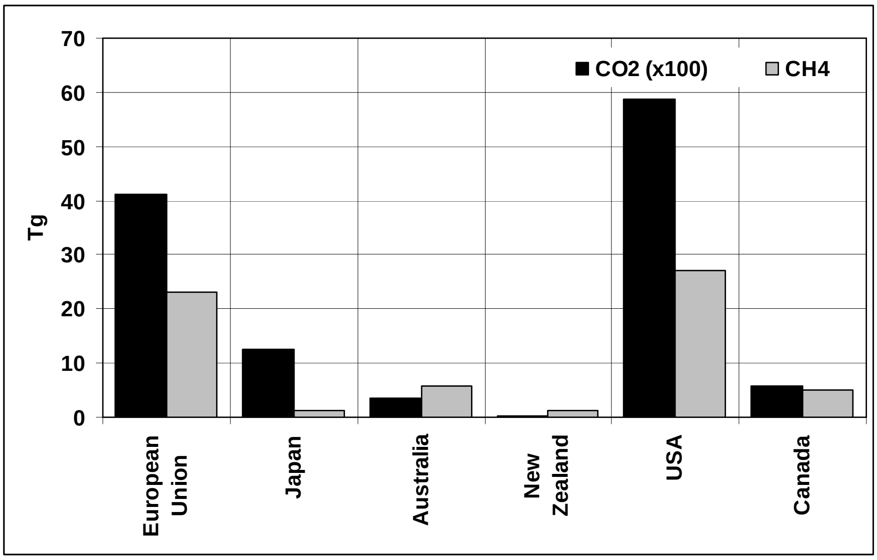

Fig. x.2. CO_2 and CH_4 emissions for the year 2000 reported under the United Nations Framework Convention on Climate Change (Source: UNFCCC);
Note: European Union includes Norway and Switzerland for comparison reasons

EDGAR emissions of CO_2 amount to 4792 Tg for the year 2000 (covering OECD Europe and Eastern Europe), while emissions of the European Union (including Switzerland and Norway) reported emissions to the UNFCCC of 4104 Tg. For methane, the respective figures are 23.6 Tg (EDGAR) and 23 Tg (UNFCCC). Both CO_2 and CH_4 are not reported to EMEP. For carbon monoxide, EMEP data submitted by countries (complemented and gap filled by independent expert estimates) has 36.5 Tg of CO for the EU25, while EDGAR (OECD Europe and Eastern Europe) accounts for 44.1 Tg.

It is beyond the scope of this chapter to conduct an in-depth assessment of uncertainties associated with national total emissions, even on a regionally aggregated scale. However, the figures above indicate, that – different reporting requirements and country allocations aside – annual total emission figures seem to be robust and discrepancies between inventories are comparatively small.

Concepts for Spatial and Temporal Dissagregation

Spatial emission patterns

National emission data, as for instance reported to the IPCC, can be further resolved by intersection with spatially explicit datasets such as land use data or digital road and railway maps. Whenever available, however, emission datasets with a better resolution (i.e. district [NUTS[4] 2] or municipality [NUTS 3] level instead of national or regional) should be used for intersection with land use data to further improve the spatial resolution. Emission data on NUTS 2 or NUTS 3 level can be generated using statistical information with the respective level of resolution as allocation parameters. Such allocation parameters can be the number of inhabitants, number of employees in different branches, number of farms and animals, etc. Appropriate parameters have to be determined for every emission activity and correlated to emission amounts to be usable as allocation parameters.

According to their geographic structure, *point*, *line* and *area* emission sources can be distinguished. Emissions from each source type require different information for spatial resolution.

Large Point Sources

Typically the following emission sources are considered large point sources. Their geographical location is clearly defined by their coordinates.

- Power plants with a thermal capacity ≥ 300 MW
- Refineries
- Nitric acid and sulphuric acid production plants
- Iron & steel plants with a production capacity of ≥ 3 Mt/a
- Paper & pulp industry with a production capacity of ≥ 100 kt/a
- Automotive paint shops with a capacity of ≥ 100000 cars per annum
- Airports with at least 100000 landing-takeoff-cycles per annum
- All other sources emitting more than 1000 Gg SO_2/NO_x or more than 300 Tg/a CO_2.

The last category includes, among others, district heating plants, waste incineration plants and various industrial production and combustion plants.

[4] NUTS - *Nomenclature des unités territoriales statistiques*, official statistical nomenclature for spatial data in the European Union

The geographical coordinates of point sources can be taken for instance from centrally available information (e.g. the *European Pollutant Emission Register*, EPER[5], respectively the upcoming *European Pollutant Release and Transfer Register*, EPRTR) or can be determined by surveys with the help of country experts. For some specific sectors or emission sources, information is as well collected in the frame of legally binding regulations, such as the EC *Large Combustion Plants Directive* (LCPD) and *Directive on Integrated Pollution Prevention and Control* (IPCC).

Line Sources

Routes of transportation of passengers and cargo are line sources: roads, railways, ships and pipelines. For these line sources, GIS based vector data are available, mostly for trans-national railways, inland waterways, highways and federal roads.

Road traffic and railway traffic

Due to the high density of roads in urban areas, urban traffic is most often treated as an area source. Rural and highway traffic is attributed to line sources with the aid of a digital European road network[6]. The average length of a street section between two points of the digital road network is 1.5 km. Emissions from railway traffic can as well be allocated using the ESRI digital European network.

Shipping

Shipping includes activities at sea, in port and on inland waterways. The coastline separates national from international shipping. Emissions from national shipping are mostly much lower than emissions from international shipping. They usually only account for 0 - 2 % of total CH_4 and N_2O emissions in European countries, but their share in CO_2 emissions may add up to 40 % in some countries. It has to be noted, that international shipping activities are projected to increase steadily and significantly. For some pollutants (e.g. SO_2) international shipping is expected to be the main single contributor by 2030.

Emissions from inland waterway transportation can be located with the aid of land use data. Emissions of SO_2, NO_x, NMVOCs and CO have previously been calculated by EMEP (Jonson 2000) with a spatial resolution of 50 × 50 km from which the spatial distribution of emissions of green-

[5] http://www.eper.ec.europa.eu/eper/
[6] http://www.esri.com/library/brochures/pdfs/transporteuro.pdf

house gases can be derived as emissions are proportional to fuel consumption.

Air traffic

Emissions from air traffic occur during LTO's (landing-and-take-off-cycles, limited by a height of 1000 m and including activities on ground like taxi and idle) and during cruise (any air traffic activity above 1000 m). LTO's are allocated to airports and attributed to the category of large point sources.

Spatial disaggregation of cruising activities might in the simplest case be based on repetitive flight schedules assuming that flight routes are always in linear distance between take-off and landing site. According to (Kalivoda 1997), much more detailed data about air traffic movements is available from the European Organisation for safety of air navigation (EUROCONTROL) which will have to be examined in order to verify their usability.

Area sources

All emission sources that can neither be attributed to point nor line sources are classified as area sources. Area sources comprise all activities which are diffuse, are attributed to a large number of small individual sources or have indistinct spatial patterns, e.g. urban traffic, household emissions and small industrial and commercial plant emissions. National emission data (and where available, data on NUTS 2 or 3 level) can be spatially resolved by intersection with CORINE land use data that are available for the European Union area with a resolution of 250 m × 250 m. This dataset was generated in the scope of the CORINE[7] - Programme. The most recent dataset for the year 2000 can be obtained from the European Topic Centre on Land Use and Spatial Information[8].

Temporal emission patterns (diurnal / seasonal / interannual)

Most often, no direct information about the temporal distribution of emissions is available from emission sources. The temporal behaviour of emission sources can be represented by surrogate statistical data like fuel use, working hours, traffic counts, and suchlike. Distinct time curves can be de-

[7] CoORdination, Information, Environment
[8] http://terrestrial.eionet.europa.eu/CLC2000

rived for individual installations, types of sources and whole source categories (see Table x.1 for an overview of indicators).

Table x.1. Overview of different indicators that can be applied to distribute emission data over time

Sector	Indicator data for monthly resolution	Indicator data for daily resolution	Indicator data for hourly resolution
Power plants	fuel use	load curves	load curves
Industrial combustion	fuel use, temperature, degree days, production	working times, holidays	working times
Commercial, institutional and residential combustion	fuel use, degree days	user behaviour	user behaviour
Refineries	oil throughput, fuel use	working times, holidays	working times, shift times
Industrial processes	production	working times, holidays	working times, shift times
Road transport	traffic counts	traffic counts	Hourly traffic counts
Air transport	LTO cycles, passenger and freight numbers	LTO cycles, passenger and freight numbers	LTO cycles, passenger and freight numbers

For stationary sources, indicator data reflecting temporal patterns of operation are most often easier to obtain, than for instance for road transport or individual industrial processes. Fig. x.3 displays exemplary graphs for the hourly resolution of power plant load for different types of days, however, the liberalisation of the energy market and the variable production of power across the European grid at any time has made it more difficult to obtain information on power plant operation recently.

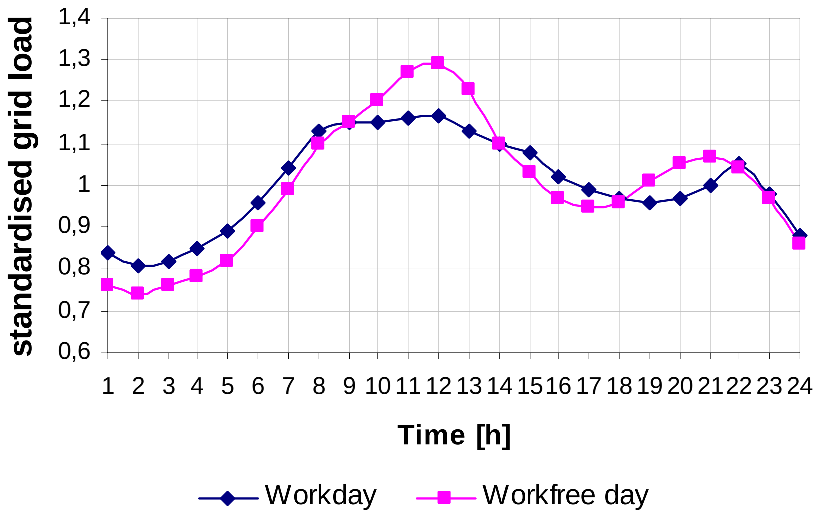

Fig. x.3. Standardised grid load time-variation curves for a workday and a workfree day in Germany (based on load data from the Union for the Co-ordination of Transmission of Electricity, UCTE)

State-of-the-art and current capabilities of fossil fuel source mapping

Top-down

One of the most used global emission inventory systems, the EDGAR[9] dataset, uses a simple top-down mapping approach to distribute country total emission estimates. EDGAR uses a population map (based on the GEIA-Li total population map) modified to allocate all population within NASA-GISS country cells and additional small entities. National emissions from fossil fuel combustion are distributed to the 1×1 degree grid, distinguishing urban and rural population in order to account for the allocation of industry and power generation emissions vs. agricultural emissions.

The advantage of this approach is obvious, as population distribution data are readily available for current and past years, and projections for fu-

[9] http://www.mnp.nl/edgar

ture development are likely reasonably accurate to allow for scenario calculations. However, the drawbacks are that in particular patterns of emissions, which are not directly related to the location of human population are not captured and point, line and area sources are virtually indistinguishable (for instance to reflect the height of the emission source for modelling).
Clearly, at the ambition level of building a global inventory and at a resolution of 1×1 degree, the top-down approach is robust and the availability of ex-post and ex-ante data for emission distribution is a positive side effect.

In most cases, a relatively coarse spatial resolution will fit the purpose of modellers, for instance for global climate change models and suchlike. But, where a more accurate representation of emissions is required, e.g. as input data for atmospheric dispersion and chemistry transport models to assess the influence of emissions on ambient air quality, more advanced methods are needed to distribute emissions. Hence, additional information to distribute emissions – again starting from national total emission inventories – is used to map emission from individual sources and source sectors. Based on methodology as described above in x.x, information on point, line and area sources is applied to allocate specific sector emissions to grid cells, an example of this can be found in Figs. x. 2 and x.3., displaying an application for The Netherlands in the frame of the CARBOEUROPE integrated project.

Fig. x.4. Example for the spatial distribution of road and rail sources and area and large point sources in the Netherlands for test case calculations in CarboEurope IP (point, line and area source data combined).

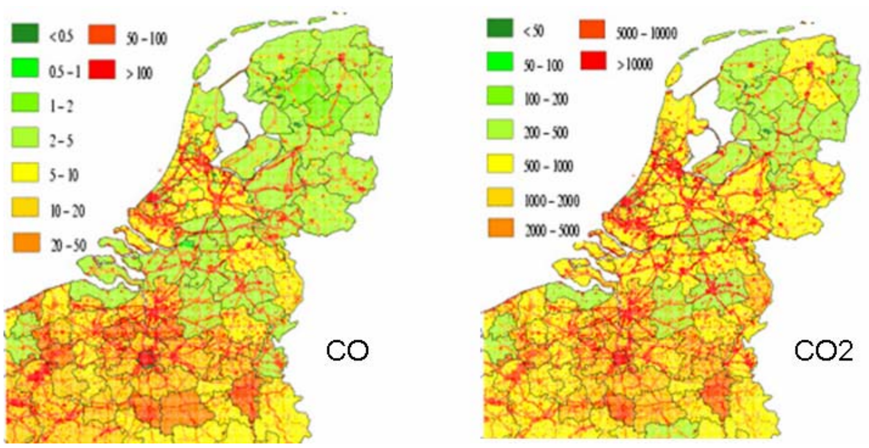

Fig. x.5. Resulting spatially resolved emissions of CO (left) and CO_2 (right) based on spatial indicator data displayed in Fig. x.4

While the strength of this more detailed approach is evident, it does require considerably more data and information such as traffic counts for major roads, location and operation of point sources and suchlike. This kind of information is most often available on national, district or municipality level, yet only ex-post and with considerable time lag; hence it is not suitable for projections.

Bottom-up

Top-down approaches will provide a sufficient level of detail for most applications and data needs. For very high resolutions, both temporal and spatial, however, using bottom-up methodology for the generation of an inventory with built-in high resolution is preferable.

This implies combining information on emission factors and activity rates already at the highest temporal resolution available and requires statistical datasets reflecting local aspects, e.g. the use of solid fuels in residential combustion or the utilisation of stationary or mobile equipment. Due to the extremely high data requirements, bottom-up approaches have rarely been applied in a consistent manner, with the exception of a few case studies, for instance the Augsburg experiment (Slemr et al. 2002), which served as test bed to validate emission models and chemistry-transport models against detailed measurements for a mid-sized town in southern Germany.

Uncertainties, gaps and robustness

In general, the uncertainties associated with the temporal and spatial resolution of emission data are closely related to those of generating emission inventories in the first place. Emission factors and activity rates, which comprise the main input factors, are of varying quality, depending on the statistical systems in place for reporting and collecting these datasets.

Various methods exist to assess the uncertainties along the chain of calculations for the generation of emission inventories, e.g. using error propagation or Monte-Carlo simulations. These have been extensively discussed in literature (see for instance Kühlwein and Friedrich 2000, or Vogel et al. 2000) and can be found as well in the IPCC report[10] Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. It is difficult to assess, to what extent the application of methods for temporal and spatial distribution of emissions increases the uncertainty

[10] http://www.ipcc-nggip.iges.or.jp/public/gp/english/

range in comparison to the uncertainty associated with the national total figures. Provided, the same datasets are used and detailed methods are applied, the overall annual emission total of for instance a bottom-up emission inventory in an hourly resolution should result in the same emission figure, with the same uncertainty bandwidth. The accuracy spatial and temporal variation, though, is entirely dependent on the quality and completeness of information used for the distribution. This quality varies by source and region, with large point source activities (e.g. power plants) in Western Europe most likely being well documented in high temporal resolution, while private road transport emission variations or sources in Eastern Europe being more uncertain.

Table x.2. Indication of uncertainty estimate for greenhouse gases.
Source: Olivier et al., 1999

		Emission Factor			**Total Emissions**		
Emission source category	**Activity data**	**CO_2**	**CH_4**	**N_2O**	**CO_2**	**CH_4**	**N_2O**
Fossil fuel use							
Fossil fuel combustion	S	S	M	M	S	M	M
Fossil fuel production	S	M	M	-	M	M	-
Industry/solvent use							
Iron & steel production	S	-	S	-	-	S	-
Non-ferro production	S	-	S	-	-	S	-
Chemicals production	S	-	S	L	-	S	M
Cement production	S	S	-	-	S	-	-
Solvent use	M	-	-	-	-	-	-
Miscellaneous	V	-	-	-	-	-	-
Landuse/waste treatment							
Agriculture	S	-	L	L	-	L	L
Animals (excreta/ruminants)	S	-	M	L	-	M	L
Biomass burning	L	S	M	L	L	L	L
Landfills	L	-	M	-	-	L	-
Agricultural waste burning	L	-	L	L	-	L	L
Uncontrolled waste burning	L	-	-	-	-	-	-
All sources	**-**	**-**	**-**	**-**	**S**	**M**	**L**

S = small (10%); M = medium (50%); L = large (100%); V = very large (>100%)
"-" not applicable/negligible

Finally, recent developments in particular in the way public power generation is operated in Europe, with the deregulation of the energy markets, has introduced an additional source of variation. Prior to the liberalisation, national power grids and electricity generation capacities were operating in a significantly more predictable environment, hence making assessments of hourly, daily, weekly or seasonal production more robust. In the new situation, the combination of time and location of power generated is difficult – if possible at all – to predict, and even ex-post evaluations are often restricted by production data being seen as commercially sensitive and thus not readily disclosed for statistical purposes. At the same time, technologies introduced for instance in telematics for road toll schemes and suchlike, which may help to gather datasets to improve the spatial and temporal resolution of traffic related emissions in the future.

Strategy towards pan-European GHG regularly updated emission mapping

Constraints on the development and setup

Overall, the methodologies for the generation of emission datasets in high temporal, spatial and substance resolution has been established based on experience gathered from work on air pollutant emissions. For the time being, improvements of the resolution are mainly limited by computing time, but even more so by the availability and quality of input data. However, some constraints have to be noted.

For instance, the data collection on large point sources needs to be improved e.g. by reporting stack heights (usually information readily available) to better distinguish high and low sources and other parameters which are vital for modellers, but are typically not included as reporting schemes are designed based on the requirements from a regulatory viewpoint. Without this information, the plume rise and thus the effective induction of substances into the atmospheric layer within the dispersion model cannot be captured properly.

Secondly, there is a clear lack of reporting requirements for activity data on a recurrent, detailed sectoral basis. These would be required to facilitate the temporal resolution of individual industrial or power generation activities and even more so, for highly variable sources such as private and public transport.

Future directions for enhanced mapping

Different trends can be observed with regard to the availability of indicators for temporal and spatial distribution. While activities on mapping and earth observation increase the resolution of e.g. land use data and the harmonisation efforts in the mapping realm such as the European INSPIRE[11] initiative provide increasingly detailed datasets which can serve to distribute emissions spatially, the development is different for information required to generate temporally resolved emission datasets. There, for instance, the deregulation of energy markets creates additional challenges for accurate spatial/temporal allocation of energy related emissions. In addition to that, reporting requirements have increased significantly due to new directives and conventions entering into force, which has led to a gradual harmonisation of reporting guidelines. In this process, the high level of sectoral detail which had marked the reporting structure for air pollutants was watered down to match the coarser and mainly energy conversion driven structure of the IPCC with significantly less detail.

Hence, two possible ways forward can be envisaged:

On the one hand, a relatively coarse distribution based on land-use data and using generic time curves to split annual total emissions into daily, weekly, monthly and seasonal patterns. This approach would be suitable for large scale modelling applications, where a higher level of detail in the input datasets would not be required. On the other hand, for local or regional applications, for instance to conduct verification experiments, it is vital to achieve greater accuracy not only with regard to the total amount of emissions over a year. In this case, a bottom-up construction of a spatially and temporally explicit emission inventory ought to be considered. This would guarantee that no detailed information on emission factors and activity rates and their spatial and temporal variation would be lost by taking the detour via an inventory compiled and these data then distributed again.

Requirements for ancillary information for scaling

As outlined above, the main requirements to improve the situation for – in particular – the temporal disaggregation of emission data would be a more comprehensive and consistent collection of activity data. In addition to that, the current trends in simplifying reporting structures to alleviate the administrative burdens of national experts, who have to report different

[11] http://inspire.jrc.it/

datasets under several conventions and directives would need to be reversed. The reason for this is straightforward: with less detailed information on emission source sectors retained in the emission inventories as they are compiled, a meaningful splitting of emissions is lacking vital indicators. If, for instance, emissions from power generation are not reported by the fuel types used in power plants, it is not possible to even distinguish base, medium and peak load plants with very different utilisation patterns.

If it is possible to include ancillary data for modelling purposes into the inventories, which are as of now driven by regulatory needs rather than the efficiency of data gathering for modelling, this could contribute to a significant improvement of model output quality, as well as reduce uncertainties to a large extent.

Conclusion

The temporal and spatial resolution of emissions from fossil fuels use are based on methodologies developed in the course of the last two decades, mainly aimed at the application to air pollutant emissions. However, the requirements are the same, as the determination of location and time of emission is a vital requirement when trying to verify model results with measurements. This is even more relevant, where measurements are marked by a high level of sophistication and detail, and where both anthropogenic sources and natural and biogenic sources may contribute to the overall ambient concentration of trace gases (for a more detailed description of the methodology, see Friedrich et al. 2003).

While methods are well developed and can be readily applied, the main problems lie in the considerable amount and detail level of information required in particular for high resolution data generation. With reporting requirements often placing considerable burdens on the national experts compiling inventories, the level of detail in reporting that would facilitate the temporal and spatial distribution of emission data are not currently included in compulsory reporting. Only within the EMEP programme, some activity data reporting requirements have been introduced in recent years to satisfy the needs of Integrated Assessment Modelling.

Regarding the quality of emission inventories in general and temporally and spatially distributed emission data in particular, uncertainties of indicator/surrogate data used for the distribution are often unknown. Typically, measurement errors are assumed to be at 20-30%, e.g. determining emission factors. In addition to that, distributed emissions are subject to errors due to averaging of results for emission factors, incomplete information and suchlike (cf. Winiwarter and Rypdal 2001 and Rypdal and Winiwarter 2001 as well).

Uncertainty analysis needs to address uncertainty in magnitude of emissions, as well as the uncertainty in trends of emissions (for future projections), and account for potential correlations between influencing factors. In this context, it is vital to be aware, that increased resolution does not always equal increased accuracy or quality of calculations.

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