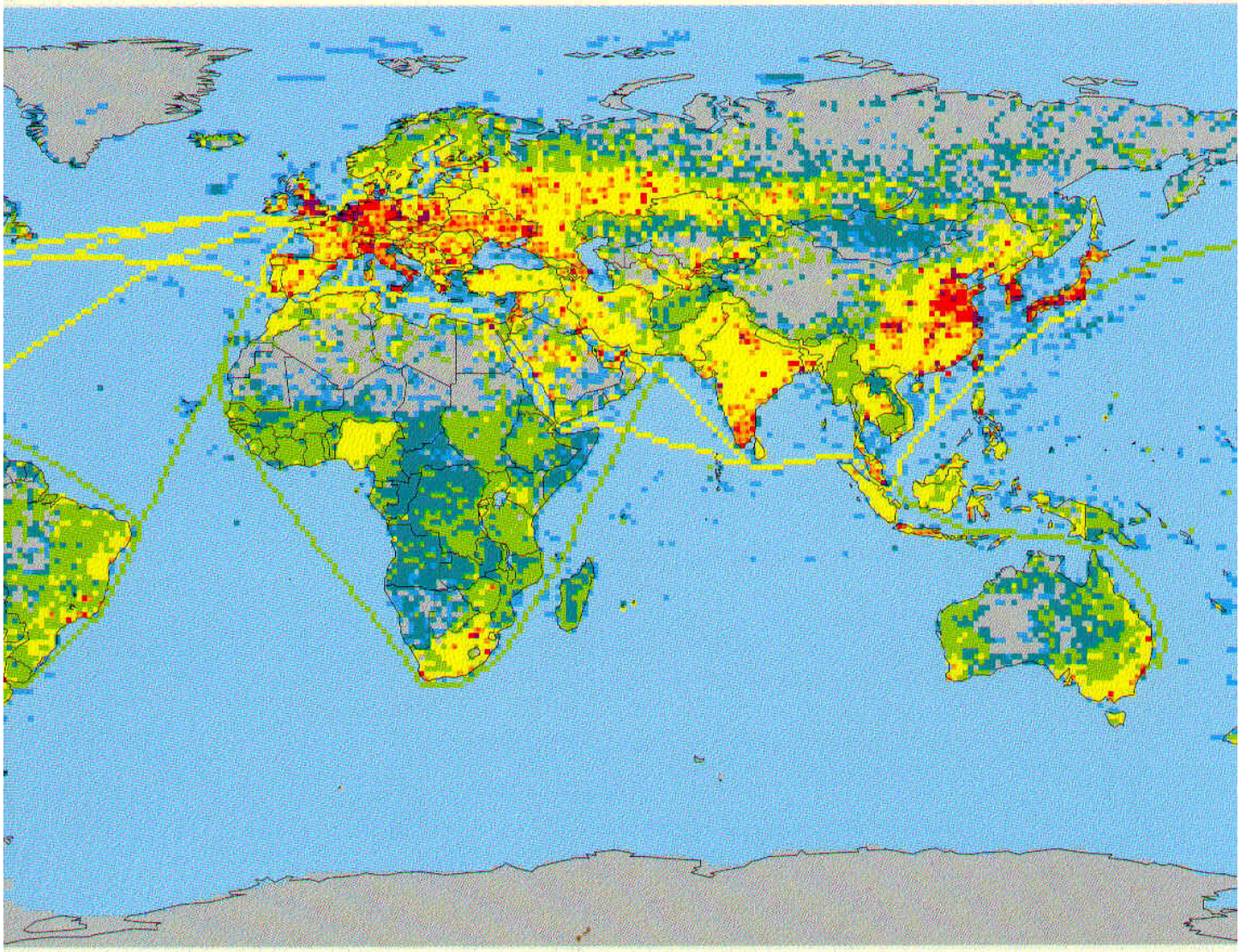
On the Quality of Global Emission Inventories

Approaches, Methodologies, Input Data and Uncertainties

Jos G.J. Olivier



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Front cover: *EDGAR 3.2 Map of Carbon Dioxide Emissions from Fossil Fuel and Biofuel Combustion in 1995**
(Grey continental areas indicate no fuel combustion. Light green indicates emissions ranging from 10 to 100 kilotonne carbon per 1x1 degree grid cell. Yellow indicates emissions between 100 kilotonne and 1 Megatonne per grid cell. Orange and red colours indicate emissions between 1 and 10 Megatonne per grid cell.)

Back cover: *World Map of Artificial Sky Brightness***
(Blue border indicates artificial sky brightness over 10% than the natural brightness. Yellow indicates artificial sky brightness equal to the natural so that the total sky brightness is doubled.)

* Including international shipping emissions and aircraft emissions below 1 km altitude. Biofuel emissions tentatively calculated at 10% of the gross emissions to account for an assumed 10% unsustainable production. More information on the Emission Database for Global Atmospheric Research (EDGAR) can be found at website: http://www.rivm.nl/env/int/coredata/edgar

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On the Quality of Global Emission Inventories

Approaches, Methodologies, Input Data and Uncertainties

Over de kwaliteit van mondiale emissie-inventarisaties

Aanpak, methodiek, gegevens en onzekerheden

(met een samenvatting in het Nederlands)

PROEFSCHRIFT

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voor Roelien

Contents

1. Introduction

This thesis deals with the quality of inventories of emissions to the atmosphere on the global scale. An emission inventory represents a compilation of estimates of amounts of one or more pollutants that have been emitted by different emission sources within a certain time period, e.g. one year. These source-specific figures refer to an area or a specific point of location and to a specific period in the past. A so-called bottom-up inventory generally contains: (a) activity data for the source (e.g. petrol consumption (kg) in road transport for a specific year), (b) emission rates, also called 'emission factors' (e.g. N_2O (kg) per kg of petrol combustion for a passenger car), and (c) the location of the emission sources. For this, data must either exist or will have to be obtained in some way.

Nevertheless, all data sources have their limitations; this applies not only to datasets made available through the literature but also to one's own measurements. So we have to deal with incomplete knowledge. This is not a new observation: scientists therefore consider uncertainty in data as a fact that must, however, be properly communicated. A key element in reports of quantitative scientific research is therefore the qualification of reported data – measured, calculated or otherwise derived – in terms of accuracy or uncertainty in a broader sense. A further implication of our limited knowledge is that the assessment of the associated uncertainty is uncertain too. Thus the uncertainty of specific estimates is uncertain as well. Within the sciences, both the primary estimate and the uncertainty estimate are based on scientifically defensible procedures that have been developed over the years in the specific disciplines. Providing a quality label is the only means to judge the results against those of other studies and to integrate these results into a larger framework. In this way the data are subject to constant review and revision when superseded by improved knowledge.

Uncertainty analysis is also receiving increasing attention in policy-oriented research, as can be observed in leading national and international publications on environmental issues (RIVM, 2001; IPCC, 2000; 2001). One of the reasons can be found in the increasing costs incurred for achieving or maintaining a specific environmental quality standard. Examples are specific levels of selected quality standards for ecosystems, human health/risks, or impacts on society (damage costs). However, the extent of emission control activities and associated costs that are being considered as requirements to guarantee or achieve the specified minimum environmental quality level are determined by two complementary aspects:

- robustness and precision of environmental pressures (e.g. air emissions);
- environmental quality targets (e.g. concentration of air pollutants or deposition fluxes to soil).

When costs increase because the cheap options have already been implemented, the public and political debaters will rightly ask for justification of the size of the *gap* between present and 'required' emission levels. Examples are found in the emissions of acidifying gases in the Netherlands or global greenhouse gas emissions. New emission reduction measures in agriculture, such as the low-ammonia emission techniques for animal housing presently considered in the Netherlands, are much more costly than measures already implemented in the past such as manure injection into the soil. In the case of greenhouse gas emissions, large emission reductions are ultimately required. However, realising these reductions is either expensive or requires large structural changes in society. Thus we are concerned here with unbiased analyses as well as assessment of the uncertainty of the environmental pressure levels (e.g. emissions to air) and of environmental impacts. This analysis is needed both for the present state and for future environmental pressure levels that are argued to be necessary to meet the environmental quality target in question.

However, emission levels and their associated uncertainty cannot simply be expressed as a single one-dimensional figure and a single confidence interval (an emission range in which the actual emissions can be found with a certain probability, e.g. 95%). The total annual emissions of a specific chemical species at national, regional or global level *as such* are often not directly relevant for the environmental quality. The strength of the emission sources varies in space and in time; the same applies to the level of environmental quality indicators. Combined with the fact that sooner or later many emitted gases or particles will react with other compounds, temporary and local exceedance of air quality standards may occur. An example is local formation of secondary emission products by chemical reactions in the air. This may happen at other locations and at another time than where and when the primary emissions occurred, which will have consequences for the first part of the environmental analysis using the so-called environmental *Pressure-State-Impact-Response* chain (or P-S-I-R chain). The environmental *pressure* of air emissions influences the *state* of concentration of pollutants in the air over space and time. This has an *impact* on the quality of the human and natural environment, which requires a *response* by defining appropriate environmental policies. For many pollutants the

distribution of the emissions is a pivotal element in determining the confidence interval of the gap between (a) the estimated *state* or *impact* variables and (b) their threshold or target values. In other words, for chemically reactive compounds, the uncertainty in the spatial and temporal distribution of total annual emissions of a geographic area (country, region, globe) is a key factor for maintaining or achieving the minimum environmental quality standards.

There are several ways of estimating annual total and area total emissions, along with more temporal and spatially detailed emission estimates, each involving different approaches, activities and aggregation levels. Here, recent insights gained from knowledge on sources of global emissions to air of direct greenhouse gases and precursors of tropospheric ozone and aerosols are discussed at various spatial and temporal aggregation levels:

- *Methodologies for estimating emissions*: so-called bottom-up and top-down approaches, of which the first are based on detailed descriptions of the sources and the second on estimates made on the basis of atmospheric data.
- *Types of emission research*: measurements, constructing inventories from activity data and emission factors, more complex modelling of (natural) emissions, estimation of source strength through so-called inverse modelling and inventory quality assessment such as verification.
- *Budgets, anthropogenic and natural emissions*: definitions, characteristics and relative importance to various compounds.

In this context, good practice in achieving the required *inventory quality* will be discussed: definition, relation with accuracy/uncertainty and quality assessments. However, the focus of the chapters will be on anthropogenic sources, bottom-up methods, global totals, gridded inventories and global/regional annual emission levels with a sectoral approach.

In this thesis practicalities are presented that determine the uncertainty and other quality aspects of global emission inventories: *availability* of activity data (years, countries), *applicability* to a specific source of emission factors and grid maps developed for a particular activity, as well as the *accuracy* or *uncertainty* of the three elements: activity data, emission factors and grid maps. The focus is on analysing how these elements influence inventory quality and how inventories can be validated and verified. This is discussed both in general terms and in practical applications, including options and priorities for improvement.

The practical applications refer to the construction of the so-called EDGAR emission inventories, which were developed as part of the Netherlands' *National Research Programme on Global Air Pollution and Climate Change* (NRP). This joint TNO-RIVM project, which started back in 1992, aimed at compiling a timely and consistent set of global anthropogenic emission inventories: the ***E**mission **D**atabase for **G**lobal **A**tmospheric **R**esearch* (Olivier *et al.*, 1994). Version 2 of this database, which covers global emissions by source for 1990, gridded at 1°x1° and at region/country level, was released in 1996 and has been extensively used worldwide, primarily by atmospheric modellers. It has triggered many questions by science and policy communities. Version 3, released in the course of 2001 and 2002, covers direct greenhouse gases for the period of 1970 to 1995 and other compounds for 1990-1995 at grid, region and country level (www.rivm.nl/env/int/coredata/edgar). It has already been used to explore emission reduction potentials and options for emission trading within the Kyoto Protocol. At present the database comprises sources of direct greenhouse gases (CO_2, CH_4, N_2O) and the so-called F-gases (HFCs, PFCs and SF_6), of ozone precursors (NO_x, CO, NMVOC, and CH_4 mentioned before) and selected aerosol precursors (SO_2, NH_3, and NO_x mentioned before). The compounds NH_3, NO_x and SO_2 also contribute to acidification of the soil.

Four key scientific questions will be investigated:

1. **How does a user define the 'quality' of a global (or national) emission inventory?** (Chapter 2)
2. **What determines the quality of a global emission inventory?** (Chapters 2 and 7)
3. **How can inventory quality be achieved in practice and expressed in quantitative terms ('uncertainty')?** (Chapters 3 to 6)
4. **What is the preferred approach for compiling a global emission inventory, given the practical limitations and the desired inventory quality?** (Chapters 7 and 8)

In Chapter 2 inventory quality will be defined and discussed in relation to methodologies and approaches for inventory construction and selected input data. The following quality aspects will be introduced: transparency, consistency, completeness, comparability and accuracy. In addition, a summary is presented of the sources of uncertainty and practical methods for estimating uncertainty in annual emissions, as well as uncertainty in trends. These all build on the special character of most bottom-up emission inventories. The role and importance of validation (= checked for the internal consistency and correctness) and verification (= comparison with independent data) of the emission inventory are also explained. Please note that in the literature these definitions are also used just the other way around. In Chapters 3 and 4 methods are presented that were used to compile a set of global grid-

ded annual inventories of anthropogenic sources for 1990, called EDGAR 2.0, and a set of global annual inventories for several years, providing historical trends for 1970-1995, called EDGAR 3.2. This includes a discussion of methodological constraints (global statistics or international country statistics, emission factors and maps for spatial distribution within countries), uncertainties in annual emissions and in trends, and validation of the emissions. Quality aspects of input data considered are:

- activity data: accuracy and completeness in years and countries;
- emission factors: quality and accuracy (also of trends over time);
- gridded maps: quality, accuracy and applicability to the source.

Chapter 5 provides an overview of existing inventories for natural sources and their uncertainty ranges. In Chapter 6 quality assessment of global anthropogenic emission inventories is then discussed by comparing two different global inventories for CO_2 and reviewing the options available for validation and verification of national and international emission inventories. Then, in Chapter 7 first a tiered approach for estimating and evaluating uncertainty in annual inventories and in emission trends in practice is presented, focussing on *national* inventories. In Section 7.3 of this chapter the uncertainties encountered when compiling *global* emission inventories – both annual and in trends – as discussed in the previous chapters are also reviewed. Here, the basic sources of uncertainty, the relationships between sources and countries that need to be considered in view of possible correlations, characteristics of input data quality and data uncertainty are discussed. In addition, examples are provided of how uncertainty can be estimated and managed in practice, and what inventory compilers and users should be aware of when constructing or using a global, or national, emission inventory. Finally, Chapter 8 summarises the answers to the first three research questions on the basis of the information presented in the previous chapters. This chapter also provides an answer to the last question on what the preferred approach is for compiling a global emission inventory. This is done in the context the practical limitations discussed here (limited human resources and limited input data quality) and the desired inventory quality for atmospheric modellers and policy-makers (a mixture of quality aspects discussed in Chapter 2). The thesis concludes with recommendations to the scientific and policy-making community to give priority to inventory quality and quality assessment.

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2. Methodology, Input Data and Inventory Quality

2.1 Approaches and characterisation of bottom-up estimates

There are two general approaches for estimating emissions for a specific area:

- *Bottom-up*: methods based on activity data, emission rates (amount of emission per unit of activity, which is called 'emission factor') and other information such as time lag in case of delayed emissions, locations etc. In some cases, direct emission measurements can be used, e.g. flue gases from the stack of a factory. In other cases, much more data for additional variables may be required, e.g. when calculating more complex modelled emissions for natural sources or delayed emissions. Models for natural sources often need to include many local environmental parameters.
- *Top-down* (also known as 'inverse modelling'): methods using atmospheric concentration measurements, atmospheric models, statistical tools and methods like chemical mass balance to invert concentration fields into parameters that provide estimates of emissions and sinks. However, for this method *a priori* emissions information is required as input, including spatial and temporal distributions, and usually models for estimating natural emissions over time.

The construction of an emission inventory may either focus on a specific year or on estimating multi-year historical trends. The inventories are based on activity data (often based on statistics), evaluation of emission factors, models for complex sources and the spatial and temporal distributions, e.g. grid-based and seasonal variation or diurnal cycles. Results of both approaches, 'bottom-up' and 'top-down', may be compared with other emission estimates, and their quality can be analysed in terms of areas of agreement and disagreement within their uncertainty ranges. In particular, a comparison of bottom-up emission inventories with top-down estimates can provide an option for independent verification if one properly takes into account the sensitivity to the *a priori* emission inputs. Thus emission research can be characterised by type of methodology:

- measurements focusing on emissions or emission factors;
- inventory construction, notably of anthropogenic sources, using bottom-up methods mentioned above;
- complex modelling of source-specific emissions or estimation of source strengths by inverse modelling;
- inventory quality assessment and validation.

When looking at the compilation of gridded global emission inventories, different bottom-up methods are possible:

1. Summation of *official national inventories* as reported to international bodies, e.g. acidifying gases and other pollutants having impacts on the continental scale such as NH_3, NO_x, SO_2, NMVOC and CO (*UN Economic Commission of Europe* (UN-ECE)) or emissions of greenhouse gases (*UN Climate Change Secretariat)*. These inventories have been compiled using bottom-up methods and most of them focus on national annual totals by source category, not on the spatial and temporal distribution.
2. *Direct estimation of emissions* based on activity data at *national* level in international statistics, emission factors and other information reported in the literature, and grid maps of human-induced activities or land use to allocate emissions on a grid. International statistics are compiled by international organisations such as the United Nations (UN) and the International Energy Agency (IEA). Examples of this method are the EDGAR inventories (RIVM and TNO) and the RAINS-ASIA inventories (IIASA) (Olivier *et al.*, 1999; Foell *et al.*, 1995).
3. Use of the *hybrid technique* of combining the two above-mentioned approaches by selecting a default global inventory (e.g. EDGAR) and replacing regions or countries, for which more accurate, country-specific inventories are available (e.g. CORINAIR inventories in Europe and Asian inventories of RAINS-ASIA). This hybrid approach has been used for the GEIA NO_x and SO_2 inventories at 1^ox1^o, which starts with concatenating available regional inventories developed at national or sub-national level by experts and adding other estimates for countries for which no specific inventory is available (e.g. Benkovitz *et al.*, 1996);
4. *Direct estimation of emissions* based on activity data for the *global total statistics* reported to international organisations and emission factors from the literature, with global total statistics divided over countries using a related surrogate variable such as gross domestic product (GDP) per country, total population per country or a similar activity for which country statistics and grid maps are available [e.g. Olivier and Bakker (2002)].
5. *Grid-based inventories*, notably for biogenic/natural sources [for example as reviewed in Olivier (2000)].

Since we limit ourselves to bottom-up methods, we will not discuss details of top-down approaches. Moreover, to estimate gridded global inventories using a top-down method requires the availability of an *a priori* inventory that can only be compiled by a bottom-up method.

2.2 Quality aspects

In all of these bottom-up methods, results should be checked for the following quality aspects: *transparency* (clarity by proper documentation of source definitions and methods and data used), *consistency* (both across years and sources, and of source definitions, methods and data), *completeness* (of sources and years), *comparability* (between countries of methods and emission factors used, and of source definitions, also called 'absence of bias'), and *accuracy* (availability of an uncertainty estimate for the emission estimates, preferably in quantitative terms). The importance of these so-called 'TCCCA' criteria have been recognised in the Guidelines of the *UN Framework Convention on Climate Change* (UNFCCC) for reporting national inventories and in the IPCC report on *Good Practice Guidance* (UNFCCC, 1999; IPCC, 2000). The five bottom-up methods mentioned above imply inherently different quality levels in terms of TCCCA.

Firstly, official *national inventories* are often difficult to assess in terms of comparability due to the country-specific methodologies applied, but will usually rank high in terms of completeness, accuracy and transparency.

Secondly, *direct estimation* of emissions based on *international country statistics* and emission factors from selected international publications should ensure a consistent approach across countries due to the harmonisation of source definitions and quality control by the international organisations that collect and compile these statistics. Therefore this approach ranks high in terms of comparability, consistency and transparency. Completeness in terms of providing global coverage is a great advantage of this approach as well. However, because of the often more aggregated approach, the uncertainty in the resulting emissions at national level may be substantial. This is caused by the limited accuracy of international activity data used and, in particular, of emission factors used for calculating emissions at country level (Olivier *et al.,* 1999; Olivier and Peters, 2002).

Thirdly, the *hybrid approach* combines the advantage of using the most complete and accurate national emission estimates whenever possible, with the drawback that in many cases the source categories distinguished differ from region to region. The latter may be reflected in the types of activity data used or the definition of the sectors. This makes it difficult, if not impossible, to compile a sectoral global emission inventory with consistent emissions across all countries within specific sectors. Thus it will rank relatively high in terms of completeness and accuracy, but low with respect to comparability and consistency.

Fourthly, the other *direct estimation of emissions* starts with activity data for *global total statistics* divided over countries using a related surrogate variable. Thus this method ensures a consistent approach across countries due to the common source definitions and the common statistics used for the subdivision per country. Therefore it ranks high in terms of comparability, consistency and transparency. Completeness in terms of providing global coverage, is a great advantage of this approach as well, if the global total figures do indeed cover all countries. However, because of the use of a *surrogate* parameter to subdivide the global total over individual countries, the uncertainty in the resulting emissions at national level is likely to be substantial. The actual uncertainty will highly depend on the appropriateness of the parameter used, i.e. the representativeness of estimating the relative strength of the actual emission source per country.

Finally, there are the *grid-based inventories*. These inventories rely heavily on the homogeneity of the parameters across the grid cell at the resolution used in these models as well as on the accuracy of the many parameter values in the datasets, e.g. temperature, amount of precipitation, soil types per grid cell, used in the emission models. They are more or less advanced in integrating all of the emission/sink sources represented in the model. Due to their characteristics, these inventories rank high in terms of transparency, consistency and comparability, but will usually rank low in terms of accuracy due to the simplifications in the model but, more important, due to the data limitations described above. The degree of completeness depends on the quality of the model and the spatial coverage of the gridded datasets used in the models.

The importance of the TCCCA criteria is valued differently when it comes to policy applications or scientific applications of emission inventories. Within the policy context, consistency over time and comparability across countries is often considered to be most important, whereas in science completeness and transparency appear to be most important, along with comparability and uncertainty of the emission estimates. Specification, i.e. quantification, of uncertainty in emission inventories is crucial in scientific analysis. Only then can different emission estimates in general and results from different approaches in particular be compared and valued. However, for policy purposes knowledge on the uncertainty of emissions per source category can also be important for defining robust environmental policies. This is especially the case when large sources addressed in these policies have a high uncertainty but also a high potential for improvement

in the emission estimates (for example by additional measurements or other research). The cost-effectiveness of source-specific emission reduction policies is directly proportional to the change resulting from improved emission estimates. In practice, this could mean that for sources with an uncertainty in the order of 100%, the reduction potential as well as its unit costs could later be proven to have doubled or diminished if in the course of time one of the extremes appears to have been the best estimate (see Figure 7.1). This information can be used both for defining robust cost-effective policies and prioritising inventory improvement programmes.

A striking observation is that people using inventories for policy applications often show much more interest in source details than scientists do. This can be explained by the wish of policy makers to allocate emissions to various economic groups in society and to explore the potential for emission reductions, for which emission estimates at a detailed source level are required. Atmospheric chemistry and transport modellers, on the other hand, are more interested in their scientific applications in distinguishing a limited number of sources that show distinct differences, for example in spatial distributions and temporal variation patterns.

For scientific applications, a clear description of data sources and methods used to construct the inventory is mandatory. As mentioned above, the documentation should also include uncertainty estimates and verification upon comparison with other studies to check for the absence of a large bias in the estimates and to identify new elements in the inventory. For national policy purposes transparency appears generally less important than for scientific applications. A notable exception is the *UN Climate Convention*, in which transparency is an important element to ensure that countries have trust in each other's national inventory and the progress they report in achieving their emission objectives.

2.3 Uncertainty estimates

A simplified standard uncertainty propagation equation for multiplication (emissions = activity * emission factor) and addition (total emissions = sum of sources and countries) can be applied to calculate the uncertainty (accuracy) in *annual emissions*. Strictly speaking, this simplification is only valid if the following three conditions are met: (1) uncertainties have a normal (i.e. Gaussian) distribution, (2) data are uncorrelated and (3) uncertainties are less than 60% (using a 2 sigma or 95% confidence interval) (IPCC, 1997). However, this will require quantitative uncertainty estimates of the underlying data and a good sense of where important correlations exist between variables. Yet, even where these conditions are not met, one can still use this approach – in the *IPCC Good Practice Guidance* report called 'Tier 1' uncertainty assessment – although some caution should be taken in the interpretation of the results (IPCC, 2000). It should be stressed that the calculated uncertainty ranges are always within the limitations of the method used to calculate the emissions. If the real emission rate characteristics are much different than modelled, for example for more complex sources, a revision of the methodology could produce a new emission estimate outside the limits of the estimated confidence interval for the uncertainty (if this does not include the structural uncertainty of the model itself). Uncertainty in input data used to calculate emissions can have conceptually different causes:

- intrinsic uncertainty due to variability, i.e. heterogeneity, of the sources;
- inexactness due to measurement errors, unclear definitions, etc.;
- unreliability due to methodological limitations such as the use of proxies or limitations in applicability of the model to the practical world;
- questions on applicability or acceptance by peers or stakeholders due to limited transparency of the dataset (definition and accuracy of data) or to limited validation of the use in emission calculation models;
- ignorance due, for example, to limited understanding of sources, unknown data processing errors and incompleteness of source categories.

Since the construction of global emission inventories often relies on national activity data and national or regional emission factors, the uncertainty at the global total level is related to the lower spatial levels. Important aspects to consider are relationships or correlations at different spatial levels and different temporal levels. The main correlations to be taken into consideration are *between countries* (when using regional or global emission factors) and *between sources* (e.g. using common emission factors, splitting total activity data over a set of sub-sources or using the same spatial distribution within countries). Often correlations can be avoided by making the uncertainty calculation at the appropriate source or regional level.

The IPCC has developed a method to estimate the uncertainty in *emission trends* - as opposed to the uncertainty in annual total emissions - using the characteristics of emission factors and activity data for different years (IPCC, 2000). Often, emission factors can be assumed to be constant in time, or they alter due to a changing abatement factor with which the fixed uncontrolled factor is multiplied. On the other hand, national statistics are usually collected through periodic questionnaires sent to identified or potential respondents. Therefore, as a rule we can say that emission factors are often correlated in time, whereas statistics

for different years are uncorrelated. These characteristics are used as the default in the IPCC Tier 1 method for estimating the trend uncertainty. The uncertainty in the emission factors is often technical (variability, unreliability, inexactness), whereas national statistics obviously show statistical uncertainty (sampling quality, ignorance) (Rypdal and Winiwarter, 2001).

2.4 The role of validation and verification

Since very much data need to be handled and since many people are often involved in compiling emission inventories – both in selecting representative emission factors and data processing – conversion and calculation errors and inconsistencies may easily slip in. Therefore it is important to *validate* the inventory (= check for the internal consistency and correctness). as part of the inventory construction process. Furthermore, several choices made by the inventory developer may introduce (unknown) bias into the inventory or into the associated uncertainty estimates. Since all bottom-up inventory compilation methods essentially rely on the same basic data i.e. activity data and measured or reported emission factors, *verification* (= comparison with independent data) of the resulting emission estimates is essential for checking the absence of a bias. These definitions are taken from IPCC (2000), but please note that in the literature these definitions are also used the other way around. Particularly in the determination of the emission factors used there is a good chance that an (unknown) bias will slip in. This includes the basic sources of uncertainty, the relationships between sources and countries that need to be considered in view of possible correlations and characteristics of the input data quality and its uncertainty. Screening the literature on available emission factors, comparisons between them and analysis of the causes for differences may assist in determining the emission factors as objectively and accurately as possible.

For estimating global emissions of a particular compound, and national or regional shares contained here, other approaches for direct emission estimates and grid-based inventories than the official national inventories are necessary in cases where not all countries report their national total emissions of this pollutant. This will happen as long as international agreements such as UNFCCC do not require *all* countries to estimate and report the national emissions of the relevant compound. Also in cases where individual countries have provided emission estimates, comparison with global direct emission inventories or grid-based inventories may be a valuable means of checking their comparability and completeness. In this respect, global emission inventories also enable the assessment of emission reduction potentials for specific countries or sources and their uncertainty. Verification of national or global emission inventories is done through:

- direct source measurements;
- comparison with global budgets based on a synthesis of all knowledge on global material flows; and,
- comparison with top-down estimates from inverse modelling.

Direct source measurements may be cost-effective in some cases of large point sources but are generally not technically or economically feasible for other sources. Comparison with global budgets is simple and should be recommended as a mandatory check, but can only be done for complete global inventories, i.e. for all countries and sources. Furthermore, it only serves as a rather crude check of large biases. This leaves us with the third option of comparison with top-down estimates. At present, there are several strong limitations on the use of inverse modelling for verification of emission inventories at national or regional levels. It is more difficult to address emissions by sector using this approach. Even distinguishing the anthropogenic from the natural part may be difficult to accomplish without additional *a priori* information such as seasonal variation of sources and their geographical distribution. For the longer-lived trace gases the signature of emission sources in the concentration fields is quite small. Limited atmospheric concentration measurements, dependency on model parameters and the potential high variability of actual emissions of some anthropogenic sources in case of episodic model calculations in a specific time period also limits the current applicability of this verification option. Benchmark studies, in which the inverse modelling results of a set of models are compared, may provide a way to assess the uncertainty generated by the model structures [e.g. the CO model intercomparison benchmark reported by Kanakidou *et al.* (1999)].

2.5 Application to global emission inventories

The next few chapters I will explore how the inventory elements discussed in this chapter apply to the construction and use of *global* emission inventories. This will be done by presenting two cases of global inventory construction, using the second bottom-up method of direct estimation of global gridded emissions of anthropogenic sources based on international statistics and emission factors selected from the literature. Quality assessment through validation and verification, and various sources and methods for estimating uncertainty in national and global inventories will then be discussed.

In the first case (Chapter 3), the focus will be on the inventory objectives and criteria used for selection of input data and emission calculation methods to calculate global emissions for a group of gases *for a single year*. This will be done by region and at grid level (EDGAR 2.0). Quality aspects discussed are the breakdown into source categories, uncertainties and verification by comparison with other studies, and documentation of the inventory in a journal article. In another article in Chapter 3 the anthropogenic emission sources of nitrogen compounds will be compared to the natural sources. Both provide examples of the use of these inventories for scientific and policy applications.

The bottom-up method is used again in Chapter 4 for the second case, where it is applied to create a comprehensive set of inventories *for a series of years* at grid level and at country levels. This is the compilation of a new global inventory of anthropogenic sources of methane for the period 1970-1995 (part of the EDGAR 3.2 set of inventories). In this case such aspects as consistency over time of methods and locations and availability and selection of input data are discussed. The resulting inventories for anthropogenic and natural sources of methane have been compared with several other global budget studies, including top-down studies. Special attention is paid to sources of uncertainty and sectoral uncertainty estimates at various spatial levels: country, regional, global and grid-cell levels. The special character of inventories of natural sources, many of which are compiled using bottom-up grid-based methods, are described in Chapter 5, including their uncertainties.

Chapter 6 presents two papers in which quality assessments of global and national anthropogenic emission inventories are discussed. In the first paper, a systematic comparison is made at country level of two global inventories for CO_2; the comparison was based on similar but different sets of international statistics, which were partly independently developed. In the paper most of the TCCCA criteria are discussed, and from the magnitude of the observed differences at country and global levels conclusions are drawn about the uncertainty in national and global emissions. Section 6.2 reviews more options available for validation and verification of national and international inventories, including an assessment of their potential and efficiency.

Chapter 7 summarises methodological and practical issues that are relevant for estimating uncertainty in national, regional and global inventories. Since uncertainty in global inventories originates to a large degree in the uncertainty in national data, a tiered approach for estimating and evaluating uncertainty in *national inventories* is presented first, both for annual and trend uncertainty. The uncertainties encountered when compiling *global inventories*, as discussed in the preceding chapters, are reviewed next. This includes the basic sources of uncertainty, the relationships between sources and countries that need to be considered in view of possible correlations and characteristics of input data quality and data uncertainty.

A large part of the contents of this thesis has been published elsewhere earlier, which shows in the layout of several chapters that are not fully harmonised, thereby reflecting their different origin.

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3. Anthropogenic Inventories for 1990: EDGAR 2.0

3.1. Introduction

In this chapter the compilation of EDGAR 2.0, a set of emission inventories of greenhouse gases and precursor gases for 1990, is presented. This is an example of the direct emission estimation approach for anthropogenic sources. Elements to be discussed:

- *Rationale* - aims at both source-specific gridded emissions and sectoral/regional emissions, which can be used for policy and scenario applications.
- *Conceptual approach* - database structure to consistently generate emissions for many different source categories both on grid and per region.
- *Methodology and data quality* - international statistics per country (global total statistics sometimes to be divided over countries), accuracy and completeness in years and countries, emission factors (quality, accuracy) and gridded maps to allocate national emissions within the country (quality, accuracy and applicability of the maps).
- *Validation and uncertainties* - comparison of global totals with IPCC estimates per main source category, and order-of-magnitude uncertainty in the resulting global and regional emission, based on uncertainty estimates for activity data and emission factors.
- *Use of the dataset for scientific and policy purposes* - atmospheric modelling, inverse modelling and examples of policy support with results from the dataset.

In Section 3.2 the general approach for the construction of the *Emission Database for Global Atmospheric Research* (EDGAR) is elaborated first, focussing on *anthropogenic* emissions and aspects common to all emission compounds and, in particular, on the direct greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The availability of regional and sectoral emissions of these three greenhouse gases enables the intercomparison of total greenhouse gas emissions and the characterisation of regions in terms of the most important compound/source combinations. For this purpose, the CO_2, CH_4 and N_2O emissions are also presented on equal footing, in terms of the so-called CO_2-equivalents (Table 11 and Figure 3 in Section 3.2).

Subsequently, Section 3.3 presents the resulting global emission inventories of the three main nitrogen compounds: NO_x (nitrogen oxides NO and NO_2), NH_3 (ammonia) and N_2O (nitrous oxide, also called laughing gas). The anthropogenic N_2O inventory discussed here is identical to the one presented in Section 3.2. The emissions of three compounds are discussed in another, integrated, fashion: i.e. from the perspective of their contribution to total global N compound emissions, including emissions from natural sources and their estimated uncertainties. Here I will show which anthropogenic source/region combination contributes most to total global anthropogenic N emissions (Figure 3 in Section 3.3). The relative importance of natural sources in total emissions of nitrogen compounds is also presented (Figure 4 in Section 3.3).

Both papers also provide examples of the use – and potential use – of the inventories in scientific and policy applications.

3.2 Sectoral emission inventories of greenhouse gases for 1990 on a per country basis as well as on 1° x 1°

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Sectoral emission inventories of greenhouse gases for 1990 on a per country basis as well as on 1°×1°

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Abstract

A set of global greenhouse gas emission inventories has been compiled per source category for the 1990 annual emissions of the direct greenhouse gases CO_2, CH_4 and N_2O, as well as of the indirect greenhouse gases (ozone precursors) CO, NO_x and NMVOC, and of SO_2. The inventories are available by sector, both on a per country/region basis and on a 1° × 1° grid. Developed by TNO and RIVM for constructing the Emission Database for Global Atmospheric Research (EDGAR) Version 2.0, in co-operation with the Global Emission Inventory Activity (GEIA) of IGAC/IGBP, the inventories meet the needs of both policy-makers and atmospheric modellers. The data sources for activity data, emission factors and grid maps are discussed with the focus on anthropogenic sources of primarily CO_2, CH_4 and N_2O. The estimates of a standard group of anthropogenic sources are presented for each compound per world region.

Keywords: Global; Emissions; Inventory; Carbon dioxide; Methane; Nitrous oxide; Greenhouse gas; Sources; Country; Sectors

1. Introduction

Aiming at the support of both policy applications and atmospheric research, Version 2.0 of the *Emission Database for Global Atmospheric Research* (EDGAR) includes data sets covering all major anthropogenic and most natural sources of greenhouse gases for 1990, both per country and on a 1°×1° latitude–longitude grid. Besides the direct greenhouse gases, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), the database also covers the three ozone precursors (and thus indirect greenhouse gases), CO, NO_x and NMVOC, as well as SO_2 and a number of ozone-depleting compounds such as CFCs. This paper focuses on the construction of the anthropogenic emission inventories of the three direct greenhouse gases. The construction of the database formed part of the Dutch *National Research Programme on Global Air Pollution and Climate Change* (NRP-MLK). Also, it is embedded in the *Global Emissions Inventory Activity* (GEIA), a component of the *International Global Atmospheric Chemistry Programme* (IGAC) Core Project of the *International Geosphere-Biosphere Programme* (IGBP) (Fig. 1). In this programme, emission inventories are developed and exchanged between the participating international groups interested in this area (Graedel et al., 1993, 1995). In the framework of GEIA, TNO and RIVM have committed themselves to co-ordinating or contributing to a number of inventories (CH_4 from fuel use and industrial processes; anthropogenic and natural N_2O emissions; anthropogenic NMVOC). GEIA has focused more on compiling the best gridded emission inventories available to date, however, not necessarily for the same base year on a per country basis or with a sectoral subdivision. However, the EDGAR system, through its structure,

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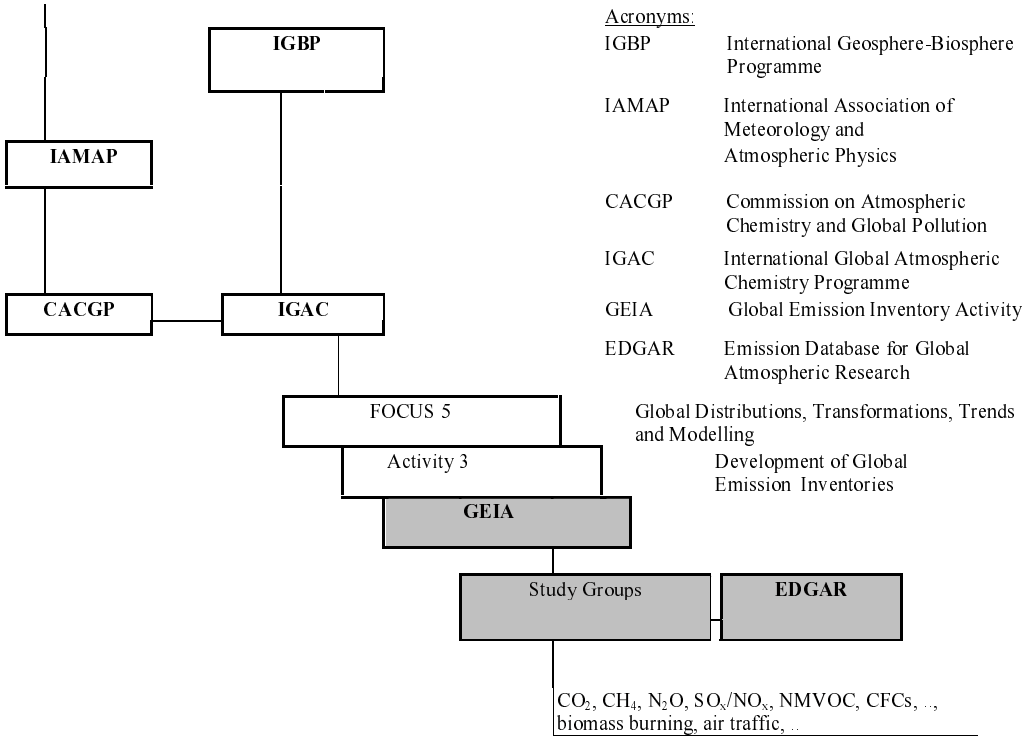

Fig. 1. International activities on global emission inventories.

provides figures for emissions and aggregated emission factors on a sectoral and per country or regional basis, while the gridded emissions are identical or quite similar to the gridded GEIA inventories. In fact, the present EDGAR inventories can be considered as GEIA inventories being converted to sectoral and country levels. The database serves as a tool for analysis and an emission generator for other atmospheric modelling groups, both within RIVM and TNO, and outside. In addition, it functions to support RIVM's climate model IMAGE, having the basic data to drive the model calculations on emissions.

2. Conceptual approach

2.1. Underlying framework

To have a flexible system to facilitate easy updates of the contents and modification, or expansion of emission sources, locations, compounds, reference years, maps, etc., we designed the database system in a modular fashion using a so-called *process approach* (Laan and Bruinsma, 1993). In general, emissions are first calculated on a country basis by multiplying activity levels by compound-specific emission factors. These emission factors define the source strength as emission per unit time and per unit activity of the process. Using specific definitions of sources and regions as groupings of (sub)processes and countries, respectively, for each compound, we are able to generate emission tables per region and source type.

In addition, we have defined a spatial allocation function to convert country emissions to the $1° \times 1°$ grid by relating a grid map to each process. In some cases of land use, where activities are not defined at the country level but directly as activities or emissions per grid cell, we have defined this map coupled to the process either as 'base level on grid', or as 'direct emissions on grid'. Currently, only one map per process can be defined (i.e. not defined for multiple years so as to take into account changes in spatial distributions in time). At present, groups of point sources are represented as gridded maps for which a conversion routine is available. Some emission sources, such as N_2O emissions from organic soils, require a more sophisticated approach, e.g. by applying a temperature-dependent model.

The *process approach* allows the required level of detail to be included through defining a tree of subprocesses, in which emission factors are inherited from the mother process if no factor is explicitly specified. Likewise, these properties can be defined at different locations (often countries), which are also hierarchically related. The world total has continents as sublocations; continents have countries (or the ocean) as a

sublocation. In the process approach, *inheritance* of emission factors and related maps is incorporated. This is a connection of emission factors and grid maps from higher process levels to subprocesses, provided no specific emission factors or maps are defined at the lower level. Inheritance of emission factors (either through the process tree or the location tree, or, subsequently, from a previous year) and related maps (via the process tree) is a very powerful tool for defining emission factors and spatial allocation functions in a very efficient and transparent way. These factors and maps are often common to many subprocesses and sublocations in a database that contains thousands of subprocesses, more than a hundred countries, and activity data for more than ten years. More details on the process approach and software implementation can be found in Olivier et al. (1994).

2.2. Data selection

The database system calculates emissions on the basis of information stored in the system: viz. activity data, emission factors and other explanatory variables. The underlying information is organised by source category, country or region or as gridded maps, as well as for a number of sources by season. The following source groups are available in the system:

- Energy production and use (by sector and fuel type).
- Biofuel use (e.g. fuelwood).
- Industrial production (e.g. cement, nitric acid, adipic acid).
- Agriculture (rice production, animal breeding, fertiliser use).
- Biomass burning (deforestation and savanna burning).
- Waste treatment (landfills, agricultural and other waste burning).
- Natural sources (soils, vegetation, oceans, wetlands).

The selection of main source categories and spatial resolution (countries and grid) was based on: (a) available statistical data, (b) quality and consistency of related data, (c) relevance for individual compounds, (d) relevance for models and policy-making and (e) possible compliance (now or in the future) with other emission inventories (particularly the gridded GEIA inventories). Countries were chosen for the availability of statistical data, including historical time-series, while the grid definition complies with that agreed upon within GEIA.

Data on national activities were selected on the basis of internationally accepted statistical data assembled by an international organisation which had performed consistency checks on the data, ensuring comparable data being used for each country and efficiently carried out future maintenance (updates). Thus, activity data were taken from the international statistical data available from, for example, IEA (energy data), UN (industrial production and consumption) and FAO (agricultural data). For some sources or countries these data were supplemented with data from UN, IISI and IFA, respectively. For biomass burning, agricultural waste burning and biogenic land-related sources we used gridded data as basic activity data, e.g. in soil types.

Emission factors are either defined uniformly for all countries, e.g. CO_2, or evaluated for individual countries, or groups of countries (regions). In the latter case we often distinguished between OECD'90 countries, Eastern Europe plus the former USSR and other non-OECD countries. In some cases, such as for road traffic, we used emission estimates for individual countries and independently defined activity levels to derive country-specific emission factors.

When available major point sources are included in Version 2.0 as distribution parameters by combining them per source category in so-called thematic maps. Thematic maps on a $1° \times 1°$ grid were used as spatial allocation function to convert, per source or per process, total country emissions to gridded emissions. A population density map was used by default when no source-specific map was available. For sources where point-source data was available for only a limited number of countries, we used this map to distribute the emissions for other countries. Unless otherwise stated, the population density map provided by Logan (1993, personal communication) was used as a default when no source-specific map was available or when point source data were only available for a few countries.

3. Construction of the data sets

3.1. Fossil fuel combustion

The energy production and consumption data sets have been constructed from data compiled by the International Energy Agency (IEA), with some minor additions/modifications made for a better spatial distribution and a more complete estimate for major source categories (IEA, 1994). This allows us to distinguish several sectors. Basically, we used the IEA energy statistics of 1971–1992 for 112 IEA countries, extended with 71 countries using IEA totals for the remaining countries and country splits according to UN data (UN, 1993, 1995). Estimates made by Samaras for road transport have been added for another six countries, while specific estimates for road transport have been added for 37 IEA/UN countries to existing

country data sets. These data sets did not specify fuel consumption at the level of road transport (Samaras, 1993). The original Samaras estimates for one year were extrapolated to the period 1971–1992 using GNP (or, if not available, population) as the index (World Bank, 1993). Total additional fuel consumption in 1990 for these 43 countries is 314 PJ or 0.3% of global total consumption of liquid fuel. Even when including these extensions, no separate energy data are available for the African countries: Botswana, Equatorial Guinea, Lesotho, Namibia and Swaziland; the Latin American countries: Dominican Republic and Puerto Rico; European mini-states like Andorra and Greenland and several small island states/territories.

For CO_2 from fossil fuel combustion we use globally uniform emission factors of coals, oil products and natural gas (Table 1). We have neglected the unoxidised fraction, which compared to Marland and Rotty (1984), is 1, 1.5 and 1% for solids, liquids and gases, respectively (IPCC default recommendations are 2, 1 and 0.5%, respectively). Furthermore we assumed here that all oxidised carbon is converted to CO_2 during combustion, neglecting fractions emitted as CO or other compounds. This essentially complies with the factors used by Andres et al. (1996) in the GEIA inventory and the factors recommended by the *Intergovernmental Panel on Climate Change* (IPCC) in the so-called Reference Approach for estimating CO_2 emissions from energy. This approach is based on the carbon content of the fuels and the fuel supply to the economy. Feedstock use of fuels and other non-energy use (such as for bitumen and lubricants) is treated as a separate sector, with emission factors calculated as a percentage (depending on the fate of the substances) of the factor for combustion as applied in the GEIA inventory (Table 1). These percentages differ only slightly from the defaults recommended by IPCC (1996). To calculate the net CO_2 emissions of the other transformation sector (e.g. coke ovens, blast furnaces, refineries) we used the same three values for coal, oil and gas, but now as negative factors, for the production of secondary fuels (coal products, gasworks gas and oil products). This was to take into account that part of the carbon input not oxidised in the sector, but in other sectors using these secondary fuels. If we had not made this net calculation, we would have counted double or neglected the losses in the transformation process itself. The CO_2 emission factors for gas flaring in oil production were calculated on a per country basis from estimated emissions by Marland et al. (1994) and crude oil production data.

Globally uniform factors for CH_4 and N_2O are also presented in Table 1. The N_2O factors have each been derived separately for combustion of coals, oil products and natural gas from existing data (Olivier, 1993). These are also recommended as default factors in the *Revised IPCC Guidelines* (IPCC, 1996). However, petrol-fuelled cars equipped with catalytic converters are known to show substantially higher emission factors for N_2O (De Soete, 1993). The use of these converters is still limited to a few countries. On the basis of information on the penetration rate of petrol-fuelled cars with catalysts, we have used a set of country-specific factors to estimate the 1971 to 1992 emissions.

Except for CO_2, N_2O and SO_2, all emission factors per fuel type in industry, power plants and the residential/commercial sectors are taken from the LOTOS database (Builtjes, 1992) for Western and Eastern European countries. These emission factors are assumed to be globally applicable. This was also the case for coke production and oil refining, for which the respective overall emission factors were defined per GJ of coal or crude oil converted. The SO_2 emission factors have been supplied by Berdowski (1995, personal communication). An exception applies to NO_x and SO_2 in Japan. Here factors representing emission-reducing measures for Japan from Kato and Akimoto (1992) have been applied. For countries within the LOTOS area and for the USA, the emission estimates from the respective LOTOS and US-EPA inventories for this source category have been converted into the EDGAR processes and entered directly into the EDGAR database.

For road transport and the evaporation of petrol from automobiles, which is by far the most important contributor in this sector, the emission estimates for NMVOC, CO, NO_x and CH_4 have been taken from Samaras (1993). An exception is formed by the USA, for which the NMVOC emission factors have been taken from the US-EPA inventory. All SO_2 emission factors for road transport have been proposed by Berdowski (1995, personal communication). The aggregate emission factors for CO, NO_x and NMVOC for jetfuel combustion by aircraft were taken from emission and fuel consumption estimates of NASA (1993), as analysed in Olivier (1995). The emission factor for CH_4 and SO_2 from aircraft was taken from Olivier (1995), the former based on a percentage of 10% methane in total VOC emissions in the LTO cycle (above 1 km methane emissions are assumed to be negligible, thus zero).

For non-CO_2 emissions from fuel combustion, the default aggregated, non-controlled sectoral emission factors by major fuel type, as recommended by the *Revised IPCC Guidelines*, are largely based on the regionally and globally aggregated sectoral emission factors by major fuel type in the EDGAR V2.0 inventories (IPCC, 1996). The actual emission factors contained in EDGAR may be more country-specific, particularly for industrialised countries; the application of emission control technology here has been assumed

Table 1
Global emission factors for CO_2, CH_4 and N_2O (g GJ^{-1} LHV) for fossil fuel combustion in EDGAR V2.0 (except for N_2O in road transport where indicated)

Compound	Sector[a]	Fuel type			Refs.
		solid	liquid	gaseous	
CO_2[a,c,d]	all sectors, except case below	93.5	70.62	56.1	IPCC (1994) and Marland and Pippin (1990)
CO_2	international marine bunkers (intern. shipping)	–	72.05	–	Andres et al. (1996)
CH_4	industry[a]	10	2	5	Builtjes (1992) and Veldt (1994)
CH_4	power generation[a]	1	3	1	Builtjes (1992) and Veldt (1994)
CH_4	total other sector[a]	300	10	–	Builtjes (1992) and Veldt (1994)
CH_4	road transport, gasoline, LPG	–	20	–	Samaras (1993)
CH_4	road transport, diesel	–	5	–	Samaras (1993)
CH_4	non-road surface transport[a]	10	50	–	Builtjes (1992) and Veldt (1994)
N_2O	all sectors/countries, except cases specified below	1.4	0.6	0.1	IPCC (1994)
N_2O	air traffic	–	3.4	–	Wiesen et al. (1994)
N_2O	Road transport 1990, USA, Canada, Japan[b]	–	4.2	–	Hawker (1990)
N_2O	Road transport 1990, Australia, Germany (Fed. Rep.)[b]	–	1.8	–	National Greenhouse Gas Inventory Committee (1994) and UBA (1994)
N_2O	Road transport 1990, former DDR[b]	–	1.3	–	UBA (1994)
N_2O	Road transport 1990, Netherlands[b]	–	1.1	–	CBS (1995)

[a] Industry: excluding the energy transformation sector; power generation: including autoproducers and cogeneration; total other sector: residential, commercial, other/non-specified; non-road surface transport: rail, inland water, other/non-specified.

[b] Emission factor for N_2O from road transport per country is the weighted average of the emission factor used for cars equipped with catalytic converters (estimated at $7 \times 0.6 = 4.2$ g/GJ) and the emission factor for uncontrolled cars (0.6 g/GJ).

[c] Ignoring the unoxidised fraction from combustion. For liquid fuels we used the weighted average factor for gasoline and diesel, whereas for marine bunker fuels this factor is 2% higher.

[d] For consumption of LPG, ethane as chemical feedstock and for other non-energetic use, of lubricants, naphtha and bitumen we used 60, 60, 50, 20 and 0% of the emission factor for liquid fuel; for consumption of gas as chemical feedstock and for other non-energetic use we used 66% of the factor for gas, based on Marland and Rotty (1984). For feedstock use of other fuels (in chemical industry) an emission factor of 0 has been assumed, except for white spirit, paraffin waxes, petroleum coke and 'other petroleum products' as well as for liquid fuel for electricity output, where we assumed full oxidation.

in a number of cases. Resulting aggregated regional emission factors for ozone precursors and SO_2 for this important sector are presented in Appendix A.

To distribute country totals for Europe and the USA, respectively, for the grid maps of fuel combustion in industry and electric power generation we used point source information and area source data from the LOTOS model and from US-EPA. Population density was used as a correlate for the other regions. The same approach was used for some industrial sources.

3.2. Fossil fuel production, handling and transport

For coal production we have split the 1990 IEA data into underground and surface mining using separate country-specific assumptions for hard coal and brown coal (mainly based on production statistics for individual coal mines by type, e.g. Mining Journal (1992)). For hard coal and brown coal mining, emission factors from Smith and Sloss (1992) were used (Table 2). When specified, emission factors for a given country (based on the type of coal and mining depth) were applied; in all other cases global default values given by Smith and Sloss (1992) were used. For crude oil production the methane emission factors have been calculated from emission estimates by Little (1989). A minor part of the total crude oil production emission comprises emissions from oil loading into marine tankers, for which we used the exported crude oil as activity data. The magnitude of this part has been estimated with emission factors for oil loading from OLF (1993). The emission factors for petroleum refining and storage at the refinery were compiled by Veldt and Berdowski (Builtjes, 1992). These emission factors account for all combustion and fugitive emissions at the refinery site. Note here that emission factors for total gas transport and distribution in EDGAR are related to total domestic supply of natural gas. These emission factors were largely based on default IPCC factors prepared by Ebert et al. (1993).

The map of global coal production distribution in 1990 was composed of four sub-maps: one for hard coal and one for brown coal, each separated into sur-

Table 2
Emission factors for methane from underground and surface coal production in 1990 in EDGAR (g CH_4 GJ^{-1} coal) (Smith and Sloss, 1992)

Hard coal underground		Hard coal surface		Brown coal underground		Brown coal surface	
World	835	World	77	World	24	World	24
USA	815	USA	75	Afghanistan	39	Afghanistan	39
Czechoslovakia	785	Australia	60	Romania	39	Brazil	39
Germany	675	UK	15	Vietnam	39	Colombia	39
Hungary	585			Australia	0.26	Czechoslovakia	39
Poland	585			Thailand	0.26	Norway	39
Romania	585					Philippines	39
Former USSR	585					Portugal	39
UK	455					Romania	39
Australia	335					Vietnam	39
South Africa	270					Australia	0.26
China	325					Germany	0.26
Rest of world	325					Algeria	0.26
						Spain	0.26
						UK	0.26
						Ireland	0.26

face (open pit) and underground mining. The coal production map was based on national production data in 1990 reported by the IEA (1994). It includes about 2100 mines in 60 countries, data primarily based on Doyle (1987), Mining Journal (1992) and Flegon (1994). The global distribution of crude oil production is primarily based on OGJ (1995), with additional data for the USSR from IPE (1990, 1994) and for the USA from EPA (1993). Data comprises approximately 3000 point sources, including offshore production platforms. The global distribution of natural gas production facilities has been compiled from maps by IPE (1990, 1994) and from figures by Sagers and Shabad (1990) for the former USSR; data comprises about 600 point sources, including offshore production. In addition to the oil production maps, a tanker-loading map has been compiled on the basis of a global survey of tanker terminals from IPE (1989). Here, about 300 point sources are included. A map for the global distribution of oil refineries has been compiled from data provided by OGJ (1995). Data for the former USSR and the Eastern European countries are from Veldt (1994) and Builtjes (1992), respectively. This map includes about 700 point sources. For more details on the construction of the fossil fuel data set and fossil fuel production and handling maps can be found in Olivier et al. (1996) and Visschedijk et al. (1999).

3.3. Biofuel combustion

For biofuel combustion, the activity levels for total biomass use per country have been taken from Hall et al. (1994). This does not apply to some industrialised countries, where IEA statistics and as secondary source the PHOXA report by Veldt (1994) were used and for countries in the Middle East, where Leach (1988) was used. This resulted in a global consumption estimate of 50 EJ for 1990, considerably higher than FAO estimates. The subdivision of the total biomass consumption into different biofuels is based on country studies, IEA and OLADE statistics. Where no subdivision was available for a country, the subdivision of a neighbouring country with the same kind of vegetation was used. Total biomass consumption was also split into residential and industrial use, based on a number of country studies and OLADE statistics. Again, when no subdivision was available, that of a neighbouring country was used. More details on the assumptions made for the sectoral and fuel split per country are presented in Olivier et al. (1999).

The emission factors for biofuels are based on IPCC (1994) and for fuelwood on 15 MJ/kg LHV (air dry; 20% moisture), resulting in 30 kg C/GJ (rounded-off) as in Hall et al. (1994). For combustion of charcoal, which has a much higher carbon content per kg, the same factor is used, since the emission factor expressed as kg C/GJ is almost the same as the factor for fuelwood. Other references are Veldt and Berdowski (1995) for CO, CH_4, N_2O and NMVOC; LOTOS (Builtjes, 1992) for default emission factors for NO_x and NH_3; Smith et al. (1993) for N_2O from fuelwood (based on a pilot study for residential stoves) and Berdowski (1995, personal communication) for SO_2. The N_2O factor for fuelwood in the first IPCC Guidelines (IPCC, 1994) is about 50% higher than the value we used. Of course, net CO_2 emissions depend on the degree of sustainable production of fuelwood, etc. As a first estimate we assumed the biofuel consumption here to represent a 10% extraction without any replacement. This allows the user to make a cor-

Table 3
EDGAR emission factors for CO_2, CH_4 and N_2O from industrial processes in 1990

Product	Emission factor	Unit	Region	Refs.
Cement (clinker)	136.0	kg CO_2-C ton^{-1}	World	Marland and Rotty (1984)
Ethene (ethylene)	247.5	g CH_4-C ton^{-1}	World	Builtjes (1992) (LOTOS)
Styrene	22.5	g CH_4-C ton^{-1}	World	Builtjes (1992) (LOTOS)
Coke production	13.171	kg CH_4-C TJ^{-1}	World	Builtjes (1992) (LOTOS)
Sinter production	375.0	g CH_4-C ton^{-1}	World	Builtjes (1992) (LOTOS)
Pig iron production (blast furnace)	675.0	g CH_4-C ton^{-1}	World	Builtjes (1992) (LOTOS)
Adipic acid	184.9	kg N_2O-N ton^{-1}	Canada	Reimer et al. (1992)
Adipic acid	110.0	kg N_2O-N ton^{-1}	USA	Reimer et al. (1992)
Adipic acid	147.1	kg N_2O-N ton^{-1}	rest of World	Reimer et al. (1992)
Nitric acid	16.0	kg N_2O-N $ton^{-1}N$	World	Reimer et al. (1992)

rection, if other assumptions for this sector are to be used.

3.4. Industrial sources

For industrial sources, most industrial production data were taken from UN (1993, 1995), since these data provide a time series from 1970 to 1990, except for a few products in the iron and steel industry taken from IISI (1994). For many commodities the time-series up to 1990 were incomplete. In those cases we extrapolated at maximum five years backward and forward in time in estimating missing values; for 1990 this happened mostly by assuming that the last known production level was kept constant in time. For some chemical products no UN data were available. Instead, production data for 1990 were compiled from various sources. Adipic acid production data are primarily based on the production capacity of plants given by Castellan et al. (1991). For manufacture of nitric acid (HNO_3), which is mainly used as feedstock in fertiliser production, global production estimates from UN statistics (UN, 1993) and industry (McCulloch, 1993, personal communication) are inconsistent. Therefore, we adopted statistics of N-fertiliser production as a correlate for nitric acid production (IFA, 1992).

The CO_2 emission factor for cement production is taken from Marland and Rotty (1984). Since cement, rather than clinker production, is used as activity data, emissions of countries having high fractions of clinker import or export or other product mixes than predominantly hydraulic cement are more uncertain. The emission factors used for industrial sources are summarised in Table 3.

For the production of adipic acid and non-ferro metals, gridded maps were compiled from global point source information (Castellan et al., 1991; ILZSG, 1994a, 1994b, 1994c; BoM, 1993; ICSG, 1995, personal communication). For the production of nitric and sulphuric acids gridded spatial distribution functions were compiled from point source data for USA and Europe contained in the NAPAP and LOTOS inventory, while using population density for all other countries.

3.5. Agriculture

Agricultural sources in EDGAR include rice paddies (CH_4), fertiliser use (N_2O) and animals (CH_4 and N_2O), while agricultural waste burning (all gases) is considered under biomass burning. Rice production levels and the area of arable land per country were taken from FAO (1991), combined with country-specific corrections for all arable-land grid cells. For emissions from animals we used animal populations per country from FAO (1991), except for caribou which were defined as numbers per grid cell (Lerner et al., 1988). Nitrogen fertiliser use was based on arable land statistics from FAO and IFA (Bouwman et al., 1995).

For rice cultivation, regional emission factors for CH_4 were taken from Kreileman and Bouwman (1994) (Table 4). Regional emission factors for methane from enteric fermentation by ruminants were taken from Gibbs and Leng (1993) (Table 5). The N_2O emission factor for the use of N fertilisers on arable land (1.25% of N content) and CH_4 and N_2O from animal waste (Table 6) are based on Bouwman et al. (1995). These are similar to the IPCC default values.

For converting agricultural emissions to the $1° \times 1°$ grid, arable land and agricultural waste- burning maps were used as compiled by Bouwman et al. (1995), whereas for rice cultivation the map of Asselmann and Crutzen (1989) was converted to the $1° \times 1°$ grid. For

Table 4
Methane emission factor for flooded rice cultivation in EDGAR V2.0 (Kreileman and Bouwman, 1994)

Region	Emission factor for wetland rice cultivation[a] ($g\ CH_4\ m^{-2}\ a^{-1}$)	Total area 1990 ($1000\ km^2$)	Area irrigated + rainfed wetland field (%)	Emission (gCH_4)
Global factor	45.5			
Canada		–	–	–
USA		11,645	100	0.5
Latin America		53,600	85	2.4
Africa		30,507	50	1.4
OECD Europe		4,056	100	0.2
Eastern Europe		1,323	100	0.1
Former SU		5,050	100	0.2
Middle East		8,942	100	0.4
India region		543,641	87	24.7
China region		404,450	99; 88 [b]	18.4
East Asia		218,626	87	9.9
Oceania		1,527	100	0.1
Japan		20,129	100	0.9
Total		1,303,494		59.3

[a] Based on 350 mg $CH_4\ m^{-2}\ day^{-1}$ and an inundated growing period of 130 days.
[b] For China and other countries in the region, respectively.

animal emissions, we used the maps for each of ten animal types by Lerner et al. (1988).

3.6. Biomass burning

Biomass burning consists of large-scale biomass burning (deforestation and savanna burning) and local fires of agricultural waste burning. Base levels for large-scale burning include the amount of carbon released in the tropics compiled by Hao et al. (1990) as distributions on a $5° \times 5°$ grid based on FAO statistics for the period 1975–1980. These distributions were converted to the EDGAR $1° \times 1°$ grid and used as the base level for calculating 1990 emissions. Thus, in EDGAR V2.0 this source is not accounted for in OECD countries, Eastern Europe or the former USSR. Revised and updated biomass inventories are currently being developed in the framework of GEIA; these include tropical and temperate burning (Graedel et al., 1995), however, are not yet available for application in Version 2 of EDGAR.

For agricultural waste burning we used estimates of carbon released per grid cell, based on regional estimates of Andreae (1991) combined with the distribution of arable land according to Olsen et al. (1983). For more details refer to Bouwman et al. (1995). To provide emission estimates for individual countries, emission estimates for grid cells related to these countries are summed, whereby an uncertainty via the allocation of border cell emissions to one specific country is introduced.

For CO_2 from large-scale biomass burning, only

Table 5
Regional emission factors for methane ($kg\ CH_4\ head^{-1}\ a^{-1}$) from enteric fermentation in EDGAR V2.0 (Gibbs and Leng, 1993)

Region	Dairy and non-dairy cattle	Buffaloes and caribous	Sheep	Goats	Camels	Pigs	Horses	Mules and asses
Canada	54.2	50	8	5	58	1.5	18	10
USA	54.2	50	8	5	58	1.5	18	10
Latin America	50.1	50	5	5	58	1.0	18	10
Africa	32.7	50	5	5	58	1.0	18	10
OECD Europe	64.2	50	8	5	58	1.5	18	10
Eastern Europe	63.4	50	8	5	58	1.5	18	10
Former SU	63.4	50	8	5	58	1.5	18	10
Middle East	32.7	50	5	5	58	1.0	18	10
India region	28.3	50	5	5	58	1.0	18	10
China region	44.5	50	5	5	58	1.0	18	10
East Asia	28.3	50	5	5	58	1.0	18	10
Oceania	54.2	50	8	5	58	1.5	18	10
Japan	54.2	50	8	5	58	1.5	18	10

Table 6
Regional emission factors for methane from animal waste in (Gibbs and Woodbury, 1993) and regional emission factors for N_2O from excreta per animal in EDGAR V2.0 (Bouwman et al., 1995)

Region	Dairy cattle	Non-dairy cattle	Buffaloes and caribous	Sheep and goats	Pigs	Asses, mules and horses	Poultry
Regional emission factors for methane (kg CH_4 head^{-1} a^{-1}) from animal waste in EDGAR V2.0							
Canada	14.0	2.8	3.0	0.4	5.6	3.7	0.3
USA	72.7	1.9	3.0	0.4	18.9	3.8	0.1
Latin America	1.9	1.0	3.0	0.2	3.0	3.8	0.1
Africa	1.4	0.5	3.0	0.2	2.3	2.1	0.1
OECD Europe	32.2	13.9	3.0	0.6	8.7	7.0	0.2
Eastern Europe	7.9	11.0	3.0	0.8	9.4	14.2	0.1
Former SU	9.1	9.3	3.0	1.0	1.9	3.2	0.1
Middle East	6.3	3.7	3.0	0.3	0.0	5.8	0.1
India region	4.6	2.3	3.0	0.2	0.7	1.1	0.1
China region	13.6	1.1	3.0	0.4	4.3	2.6	0.1
East Asia	68.4	6.6	3.0	0.4	7.3	3.7	0.1
Oceania	5.1	1.5	3.0	0.4	39.1	3.7	0.1
Japan	82.8	15.7	3.0	0.4	15.2	3.7	0.4

Region	Dairy cattle	Non-dairy cattle	Buffaloes, horses and caribous	Sheep	Goats	Pigs	Camels	Poultry
Regional emission factors for N_2O from excreta per animal (kg N head^{-1} a^{-1}) in EDGAR V2.0								
Region I[a]	80	45	45	10	9	11	55	0.5
Region II[b]	60	40	45	10	9	11	55	0.5

[a] Region I: Canada, USA, OECD Europe, Israel, Eastern Europe, former SU, Japan, Australia, New Zealand.
[b] Region II: Latin America, Africa, Middle East (excl. Israel), India region, China region, East Asia, non-OECD Oceania.

deforestation is accounted for. Carbon losses from savanna burning and agricultural waste burning do not contribute to net emissions, since the vegetation is regrown in an average period of 1 to 2 years. For biomass burning and agricultural waste burning, the emission factor for N_2O was taken from Crutzen and Andreae (1990) and described in detail in Bouwman et al. (1995). The NMVOC, CO and CH_4 emission factors form these sources have all been taken from Veldt and Berdowski (1995), while for SO_2 and NO_x the emission factors came from Andreae (1991) (Table 7).

3.7. Waste treatment

The remaining waste treatment sources include landfills (CH_4) and uncontrolled waste burning (NMVOC). Waste water and sewage treatment sources of methane have not been included in Version 2.0 because to date there are no representative spatial emission estimates. The landfilled amounts of waste are based on per-country estimates of waste production per capita and the fraction disposed of by landfilling, as specified for the 13 regions in RIVM's climate model IMAGE 2. For this, data was taken from Subak et al. (1992) as described in Kreileman and Bouwman (1994). Amounts of uncontrolled waste burning are based on per-country estimates of the amount combusted per capita. Regional emission factors for CH_4 from landfills were derived from Subak et al. (1992) (Table 8).

3.8. Natural sources

Natural sources different considerably: natural soils, natural vegetation, wetlands and oceans are all sources of greenhouse gas emissions, for some of which emission estimates for specific compounds are available. Because of the complex nature of these sources most of them are either defined as base levels on grid or directly as emissions per grid cell. They have been added as emission maps on grid wherever readily available.

Table 7
Global emission factors for CH_4 and N_2O from biomass burning in EDGAR V2.0 (Crutzen and Andreae, 1990; Veldt and Berdowski, 1995)

Source/compound	Emission factor[a]
Methane (g CH_4 kg^{-1} C)	
Savanna burning	13.3
Deforestation	13.3
Agricultural waste burning	13.3
Nitrous oxide (g N_2O-N ton^{-1} C)	
Savanna burning	0.042
Deforestation	0.070
Agricultural waste burning	0.105

[a] Using a CH_4-C/CO_2-C ratio of 0.01 and a C/N ratio of 0.006, 0.01 and 0.015 for savanna burning, deforestation and agricultural waste burning, respectively.

Table 8
Regional emission factors for methane from landfills in EDGAR V2.0 (Subak et al., 1992)

Region	CH_4 emissions acc. Subak et al. (1992)[a] (Gg CH_4)	Population acc. World Bank (1990) (million)	Regional emission factor (kg CH_4 cap^{-1} a^{-1})
Canada	1093	26	41.030
USA	9966	249	39.866
Latin America	2684	448	5.991
Africa	1758	642	2.738
OECD Europe	6298	378	16.674
Eastern Europe	1488	123	12.059
Former SU (CIs)	3085	289	10.662
Middle East	1915	203	9.425
India region	1966	1171	1.679
China region	2572	1248	2.060
East Asia	1144	371	3.086
Oceania	1037	23	45.496
Japan	721	124	5.836
Total	35727	5297	–

[a] Based on the following assumptions: waste generation of 1.6, 1.0, 0.6 and 0.5 kg/cap/day; landfilled fractions 80, 66, 87 and 80%; degradable organic carbon (DOC) fractions of 21, 19, 17 and 13% in Canada/USA, other OECD, CIS/Eastern Europe and developing countries, respectively.

4. Key differences between emission factors and the IPCC guidelines

The IPCC methodology for estimating CO_2 emissions from energy is based on the carbon content of the fuels and the fuel supply to the economy. The IPCC methodology for estimating fuel-related emissions is based on fuel statistics for apparent consumption and emission factors by fuel type. The IPCC Guidelines have chosen Tiers, a tiered approach to provide for the different levels of detail in the methodology. The level of detail chosen in the Tier 1 method is formed by three types of fuel: solid, liquid and gaseous fossil fuels. In the Tier 2 method, emission factors are used for each detailed type of fuel in use in a country. As shown in Table 1, the emission factors used for EDGAR V2.0 are fairly similar to those of IPCC Tier 1, except for minor differences (e.g. the non-oxidised fraction and some fractions quickly oxidised in fuels used as chemical feedstock). For cement production, factors are equal, however these are based on cement production rather than on clinker production. Emission factors in Version 2.0 for methane from agricultural sources and landfills are based on regional, rather than country-specific, estimates, while N_2O factors are very similar except that they do not include indirect emissions due to deposition and runoff of nitrogen from, for example, ammonia emissions. Note that for biomass burning and biofuel use, non-CO_2 emission factors in EDGAR V2.0 are different from the Revised IPCC defaults. We also recall that for non-CO_2 emission factors for fossil fuel combustion, the EDGAR V2.0 data may be somewhat more region- and country-specific than the global, uncontrolled default emission factors of the *Revised IPCC Guidelines* (IPCC, 1996).

5. Results and uncertainties

5.1. Results

The results of calculating all anthropogenic sources for CO_2 are presented in Table 9. The total emissions in 1990 amount to 24.8 Pg CO_2 or 6.8 Pg C, including 0.5 Pg CO_2 biofuel consumption assuming that 10% of woodfuel, etc., collection and 10% of wood waste generation in OECD regions is done in a non-sustainable way. In addition, the calculated CO_2 emissions assume that all carbon is fully oxidised during combustion to CO_2. When correcting for the fraction that not fully oxidised (e.g. to CO), fossil fuel emissions would be 0.5 to 1% lower, whereas biofuel and deforestation emissions would be about 10% lower. We recall that CO_2 emissions from savanna burning and agricultural waste burning are not accounted for, since the regrowth in 1 or 2 years time compensates for this. Most emissions are energy-related: roughly speaking 70% of this total stems from fossil fuel combustion, 3% from non-energetic use of fossil fuels (e.g. lubricants, bitumen or chemical feedstock), 1% from associated gas flaring (oil production) and almost 20% from biofuel use (predominantly fuelwood) when assuming 100% non-sustainability. In addition, 2% originates from cement production and in our estimate (Hao et al., 1990) about 6% represents the net contri-

Table 9
Global estimates of CO_2 emissions per region and source in 1990 (Tg CO_2 a^{-1}). All sectors: 100% oxidation to CO_2 was assumed, except for non-energy and feedstock use of fuels; to be corrected for the fraction not oxidized to CO_2, which is typically 0.5–2% for fossil fuel combustion and about 10% for biofuel combustion and large scale biomass burning. Other transf. sector: notably refineries, coke ovens, blast furnaces, etc., including fuel combustion for fuel extraction. Net CO_2 emissions from this sector have been calculated from carbon content in fuel inputs minus content in fuels produced, plus emission from fuel combustion. Biofuel: 10% non-sustainable production was assumed here; to be corrected for actual percentage of sustainable consumption. Non-energy use: consumption of lubricants, waxes, etc., in industry, transport, etc. Feedstock use: consumption of naphtha, etc., as chemical feedstock in industry. The number of figures in the estimates do not represent the actual accuracy of each estimate (see Table 16 for derivation of the estimated uncertainty ranges), but are shown to provide better insight to the relative contributions within each region or sector

Source/sub-sector	Total	Can.	USA	Lat. Am.	Africa	W. Eur.	E. Eur.	CIS	M. East	India×	China×	E. Asia	Ocean.	Japan	Int. ship
Total	24275.3	477.5	5137.3	1926.0	1433.9	3480.3	1008.6	3578.5	881.8	969.5	2740.4	877.3	310.4	1104.1	349.8
o.w.															
Fossil fuel: combustion	20115.4	417.9	4721.4	917.2	665.7	3089.5	960.1	3400.3	752.9	641.9	2403.8	548.2	287.6	959.2	349.8
o.w. industry	4010.9	69.7	648.8	179.5	104.4	442.2	130.5	884.4	100.6	198.8	941.9	111.6	40.8	157.8	0.0
o.w. power generation	6638.3	92.9	1773.4	153.1	249.5	945.9	444.4	1296.8	180.6	257.7	677.1	125.3	128.0	313.7	0.0
o.w. other transf. sector	1623.6	47.0	258.2	135.6	138.8	256.9	156.0	183.9	103.0	28.1	113.4	55.0	24.7	123.1	0.0
o.w. residentials, etc.	3343.3	80.0	603.3	130.2	59.7	660.8	151.0	644.6	207.3	57.2	492.6	110.3	15.2	131.0	0.0
o.w. road transport	3261.1	97.2	1160.7	282.2	97.1	659.7	68.0	222.2	131.4	75.1	103.9	114.1	63.0	186.3	0.0
o.w. non-road land transport	343.4	18.1	50.6	11.6	2.0	33.1	5.0	101.7	1.4	17.5	61.9	9.7	5.9	24.9	0.0
o.w. air (domestic+intern.)	544.9	13.0	226.5	24.9	14.2	90.9	5.1	66.8	28.6	7.6	12.9	22.2	10.0	22.3	0.0
o.w. international shipping	349.8														349.8
Fossil fuel: non-combustion	1206.8	44.8	331.5	64.6	73.3	268.6	21.1	104.3	77.3	30.6	22.8	50.5	14.9	102.7	0.0
o.w. non-energy use	334.0	14.9	180.5	0.9	0.0	87.9	11.6	0.0	3.1	0.0	0.0	0.0	8.4	26.5	0.0
o.w. feedstock use	613.0	25.6	143.2	42.5	5.8	155.4	8.4	80.5	18.7	18.5	10.6	23.3	4.2	76.1	0.0
o.w. gas flaring	259.9	4.3	7.8	21.2	67.5	25.3	1.1	23.8	55.4	12.1	12.1	27.2	2.2	0.0	0.0
Biofuel	545.6	8.9	49.0	40.2	97.1	22.1	2.8	5.5	13.2	136.9	115.9	49.9	4.0	0.1	0.0
o.w. industry	117.8	8.4	39.8	7.3	5.8	20.8	2.5	5.0	1.7	12.4	5.4	5.8	2.8	0.1	0.0
o.w. other transf. sector	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0
o.w. residentials, etc.	427.0	0.5	9.2	33.0	91.3	1.2	0.3	0.6	11.5	124.5	110.5	43.2	1.1	0.0	0.0
Industrial processes	570.1	5.9	35.4	42.1	25.9	100.0	24.7	68.5	38.2	27.5	115.1	40.9	3.9	42.1	0.0
o.w. cement	570.1	5.9	35.4	42.1	25.9	100.0	24.7	68.5	38.2	27.5	115.1	40.9	3.9	42.1	0.0
Landuse/waste treatment	1837.4	0.0	0.0	861.8	571.9	0.0	0.0	0.0	0.3	132.7	82.9	187.8	0.0	0.0	0.0
o.w deforestation	1837.4	0.0	0.0	861.8	571.9	0.0	0.0	0.0	0.3	132.7	82.9	187.8	0.0	0.0	0.0
o.w. Savannah burning	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

bution from large-scale biomass burning (deforestation). Within fossil fuel use, electric power generation is responsible for one-third of the CO_2 emissions, with other industrial sources as the second largest emitters. This can be explained from the fact that in most regions coal is in predominant use in these sectors. Fuel combustion in the residential sector accounts for almost one quarter of total anthropogenic emissions if we include emissions from biofuel use. This occurs predominantly in India, China and Africa, at 100% non-sustainable production. Cement emissions are concentrated in China, Western Europe and the former USSR, whereas large-scale biomass burning emissions stem mainly from Latin America and Africa. Fig. 2(a) shows the CO_2 emissions from fossil fuel use on a $1° \times 1°$ grid. As expected, industrialised regions such as the USA, OECD Europe and the former USSR have the largest shares (12 to 19% in global total CO_2 emissions). The China region also contributes substantially (13%), due to the high share in global coal consumption and residential biofuel use. However, due to the large amounts of large-scale biomass burning and biofuel use, the regions Africa, Latin America and India also have fairly large shares of about 8% each.

In the EDGAR database the global total for anthropogenic CH_4 emissions amounts to 320 Tg for 1990 (Table 10). This figure is consistent with that stated by the IPCC (320 versus 360 Tg). Fig. 2(b) shows the CH_4 emissions on a $1° \times 1°$ grid. Although the division over the various emission source categories differs between the regions, there are no obvious dominant regions in terms of total CH_4 emissions. When the

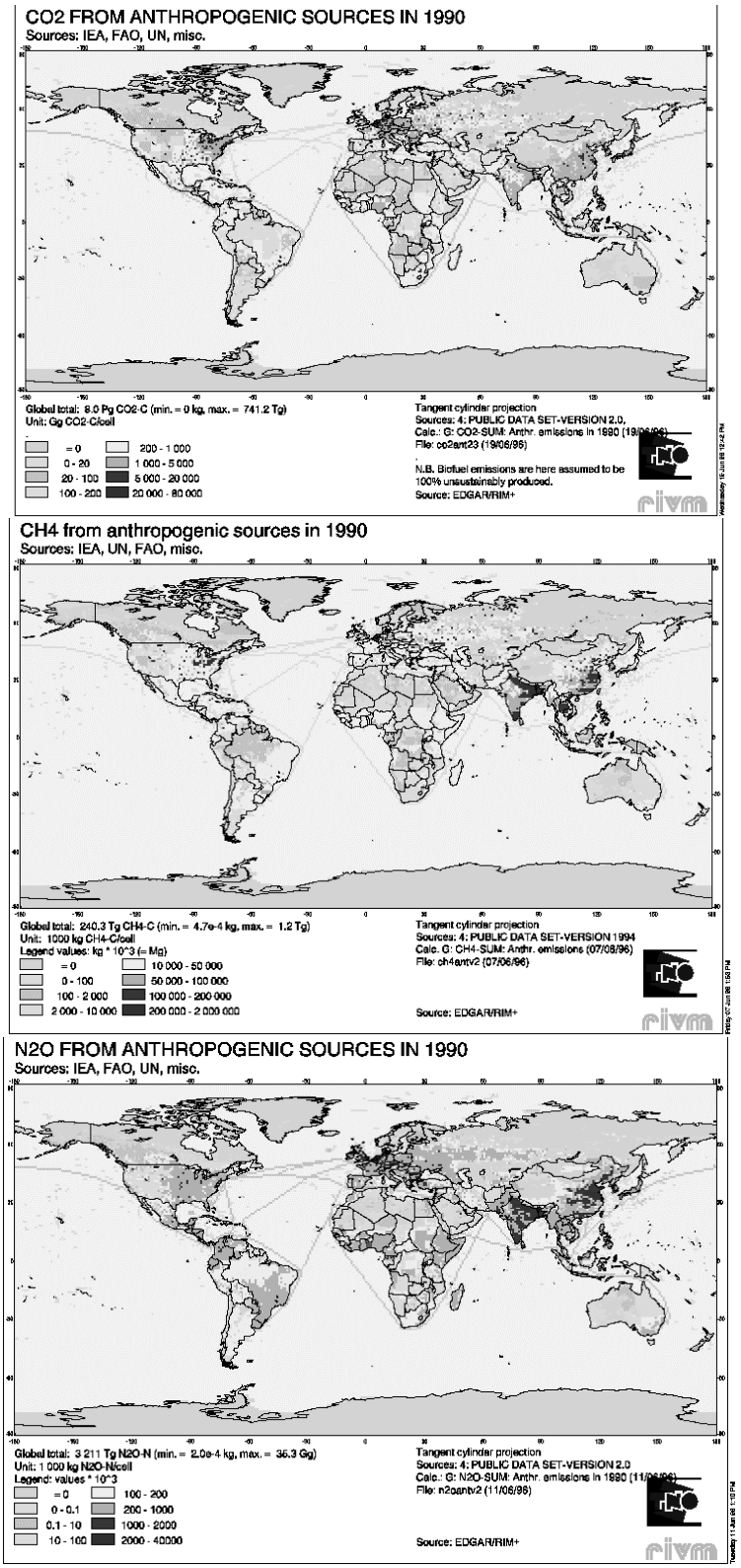

Fig. 2. Spatial distribution of global anthropogenic emissions of (a) CO_2, (b) CH_4 and (c) N_2O in 1990 (below 1 km altitude).

Table 10
Global estimates of CH_4 emissions per region and source in 1990 (Gg CH_4 a^{-1}). Other transf. sector: notably refineries, coke ovens, blast furnaces, etc., including fuel combustion for fuel extraction. The CH_4 emissions from this sector are the sum of combustion and non-combustion emissions. Oil handling: tanker loading. Gas transmission: sum of transport and distribution. Biomass burning: sum of deforestation and savanna burning. Enteric fermentation: emissions from ruminants. The number of figures in the estimates do not represent the actual accuracy of each estimate (see Table 16 for derivation of the estimated uncertainty ranges), but are shown to provide better insight to the relative contributions within each region or sector

Source/sub-sector	Total	Can.	USA	Lat. Am.	Africa	W. Eur.	E. Eur.	CIS	M. East	India +	China +	E. Asia	Ocean.	Japan	Int. ship
Total	320.2	3.9	41.6	32.4	26.8	23.4	10.8	47.0	10.3	49.9	46.7	18.6	5.7	3.2	0.0
o.w.															
Fossil fuel: combustion	4.8	0.0	0.5	0.1	0.1	0.6	0.3	0.9	0.1	0.1	1.6	0.2	0.0	0.1	0.0
o.w. industry	0.4	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0
o.w. power generation	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
o.w. other transf. sector	0.4	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
o.w. residentials, etc.	3.1	0.0	0.1	0.0	0.0	0.4	0.3	0.7	0.0	0.0	1.4	0.1	0.0	0.0	0.0
o.w. road transport	0.7	0.0	0.2	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
o.w. non-road land transport	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
o.w. air (domestic + intern.)	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
o.w. international shipping	0.0														0.0
Fossil fuel: production	89.3	1.6	21.3	2.7	2.9	4.8	5.3	31.0	4.5	1.3	9.8	2.3	1.2	0.6	0.0
o.w. coal production	37.8	0.2	12.0	0.4	1.3	3.6	3.4	5.6	0.1	0.9	9.1	0.2	0.9	0.2	0.0
o.w. oil production	7.6	0.2	1.0	1.3	1.1	0.1	0.0	1.9	0.9	0.1	0.5	0.4	0.1	0.0	0.0
o.w. oil handling	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
o.w. gas production	17.6	0.3	1.3	0.2	0.2	0.1	0.5	10.9	2.5	0.1	0.0	1.4	0.1	0.0	0.0
o.w. gas transmission	26.1	0.9	7.1	0.7	0.3	0.9	1.4	12.6	0.8	0.2	0.1	0.3	0.2	0.4	0.0
Biofuel	14.1	0.0	0.4	1.0	3.8	0.1	0.0	0.0	0.3	4.0	2.8	1.6	0.0	0.0	0.0
o.w. industry	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
o.w. residentials	13.9	0.0	0.3	1.0	3.8	0.0	0.0	0.0	0.3	4.0	2.8	1.6	0.0	0.0	0.0
Industrial processes	0.8	0.0	0.1	0.0	0.0	0.2	0.0	0.2	0.0	0.0	0.1	0.0	0.0	0.1	0.0
o.w. iron and steel	0.8	0.0	0.1	0.0	0.0	0.1	0.0	0.2	0.0	0.0	0.1	0.0	0.0	0.1	0.0
o.w. chemicals	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Landuse/waste treatment	211.4	2.2	19.2	28.5	20.0	17.8	5.1	15.0	5.4	44.5	32.5	14.4	4.4	2.5	0.0
o.w. rice cultivation	59.8	0.0	0.5	2.4	1.4	0.2	0.0	0.3	0.4	24.6	18.9	10.0	0.1	0.9	0.0
o.w. enteric fermentation	92.6	0.8	7.7	18.4	9.6	10.4	3.3	10.5	2.1	14.6	9.2	1.9	3.2	0.7	0.0
o.w. biomass burning	11.5	0.0	0.0	4.0	6.1	0.0	0.0	0.0	0.0	0.4	0.3	0.6	0.0	0.0	0.0
o.w. landfills	35.7	1.1	10.0	2.7	1.8	6.3	1.5	3.1	1.9	2.0	2.6	1.1	1.0	0.7	0.0
o.w. agricultural waste burning	11.9	0.2	1.0	1.0	1.1	1.0	0.2	1.1	0.9	2.8	1.5	0.8	0.1	0.1	0.0

different emission source categories from Table 10 are considered, six major categories can be distinguished. In order of decreasing importance these include: enteric fermentation, rice paddies, landfills, the natural gas industry, coal mining and biomass burning.

The results for N_2O are presented in Table 11 and the spatial distribution in Fig. 2(c). The total anthropogenic emissions in 1990 of these sources are 5.0 Tg N_2O or 3.2 Tg N_2O-N, including emissions related to the post-burning effects of deforestation. Most emissions are related to land use and waste treatment: about three-quarters of the total stems from fertiliser use on arable lands, animal excreta and from biomass burning (predominantly deforestation, since we included an estimate of post-burning emissions of 0.4 Tg N_2O-N). Industrial processes account for 14% and the remainder is mainly related to fuel combustion. Because of the high fraction of emissions from agriculture and other land-use sources, it is not surprising that the regions of India, Latin America and China show the highest shares in the regional split. The second largest group consists of OECD Europe, Africa, USA and the former USSR, all of which contribute about 10% in anthropogenic N_2O emissions. Other regions have relatively low emissions.

From Tables 9–11 one can derive per compound the most important sources per region and which are the dominant regions globally or per source type.

Table 11
Global estimates of N_2O emissions per region and source in 1990 (Gg N_2O-N a^{-1}). Other transf. sector: notably refineries, coke ovens, blast furnaces, etc., including fuel combustion for fuel extraction. Arable land: emissions due to fertilizers use, excluding background emission of N_2O of about 0.9 Tg N globally. Animals: animal waste. Biomass burning: sum of deforestation and savanna burning. Post-burn effects: delayed emissions related to deforestation. Natural emissions: natural soils: global total emissions 6.6 Tg N_2O-N (including 1.4 Tg N_2O-N background emissions from grasslands). Oceans: global total net emissions 3.6 Tg N_2O-N (net, i.e. including negative oceanic sinks). The number of figures in the estimates do not represent the actual accuracy of each estimate (see Table 16 for derivation of the estimated uncertainty ranges), but are shown to provide better insight to the relative contributions within each region or sector

Source/sub-sector	Total	Can.	USA	Lat. Am.	Africa	W. Eur.	E. Eur.	CIS	M. East	India+	China+	E. Asia	Ocean.	Japan	Int. ship
Total	3214.2	50.5	353.7	462.1	357.7	366.2	122.8	294.3	85.1	400.0	501.2	134.7	50.0	34.0	1.9
o.w.															
Fossil fuel	165.9	4.8	60.3	4.5	4.0	20.9	6.9	17.5	3.4	5.2	22.0	3.4	2.4	8.7	1.9
o.w. industry	31.0	0.4	3.7	1.2	0.9	3.8	0.9	4.5	0.5	1.9	10.0	1.0	0.2	2.0	0.0
o.w. power generation	49.6	0.8	15.3	0.8	2.0	7.7	3.7	7.0	0.7	2.2	6.1	0.8	1.1	1.3	0.0
o.w. other transf. sector	4.9	0.1	1.0	0.3	0.1	1.1	0.8	0.4	0.3	0.1	0.3	0.1	0.1	0.2	0.0
o.w. residentials, etc.	17.5	0.2	1.8	0.6	0.3	3.0	1.1	3.4	1.0	0.3	4.4	0.7	0.1	0.6	0.0
o.w. road transport	55.8	3.1	37.1	1.5	0.5	4.6	0.4	1.1	0.7	0.4	0.6	0.6	0.8	4.4	0.0
o.w. non-road land transport	2.1	0.1	0.3	0.1	0.0	0.2	0.0	0.6	0.0	0.1	0.5	0.1	0.0	0.1	0.0
o.w. air (domestic + intern.)	2.9	0.1	1.2	0.1	0.1	0.5	0.0	0.4	0.2	0.0	0.1	0.1	0.1	0.1	0.0
o.w. international shipping	1.9														1.9
Biofuel	60.3	0.7	3.9	4.5	11.5	1.5	0.2	0.5	1.5	16.0	13.8	5.9	0.3	0.0	0.0
o.w. industry	8.6	0.6	2.8	0.5	0.5	1.3	0.2	0.4	0.1	1.0	0.4	0.7	0.1	0.0	0.0
o.w. residentials, etc.	51.6	0.1	1.1	4.0	11.0	0.2	0.0	0.1	1.4	15.1	13.4	5.2	0.1	0.0	0.0
Industrial processes	458.3	20.7	90.2	21.1	5.0	122.5	40.4	58.3	7.5	19.5	48.6	12.4	0.6	11.5	0.0
o.w. adipic acid	282.3	14.8	66.7	14.1	0.0	99.7	29.4	29.4	0.0	0.0	14.1	4.7	0.0	9.4	0.0
o.w. nitric acid	176.0	5.9	23.5	7.0	5.0	22.9	11.0	28.9	7.5	19.5	34.4	7.6	0.6	2.1	0.0
Landuse/waste treatment	2529.7	24.3	199.2	432.0	337.3	221.3	75.4	218.0	72.7	359.2	416.8	113.0	46.7	13.7	0.0
o.w. arable land	963.4	14.5	126.8	47.2	26.3	129.8	41.9	109.2	30.8	123.1	257.8	42.0	6.2	7.7	0.0
o.w. animals	1021.3	8.0	64.7	177.9	137.6	83.7	31.6	99.8	34.8	185.1	129.1	23.8	39.6	5.6	0.0
o.w. deforestation	35.1	0.0	0.0	16.5	10.9	0.0	0.0	0.0	0.0	2.5	1.6	3.6	0.0	0.0	0.0
o.w. post-burn effects def.	360.9	0.0	0.0	169.3	112.3	0.0	0.0	0.0	0.1	26.1	16.3	36.9	0.0	0.0	0.0
o.w. savannah burning	55.6	0.0	0.0	13.0	41.4	0.0	0.0	0.0	0.0	0.2	0.5	0.5	0.0	0.0	0.0
o.w. agricultural waste burning	93.4	1.9	7.8	8.0	8.7	7.7	1.9	9.0	7.0	22.2	11.6	6.1	0.9	0.5	0.0

Furthermore, major differences in emission sector profiles between regions and the possible emission reduction per region feasible when considering sector-specific reduction options, can also be derived per compound. To put the three inventories into the perspective of greenhouse gas emissions, we have converted all emissions to CO_2-eq. using global warming potentials of 21 and 310 for CH_4 and N_2O, respectively (Fig. 3 and Table 12). Although there is a substantial uncertainty related to all emissions other than CO_2 from fossil fuel combustion, the overall picture emerging is the following:

- Fossil-fuel related emissions, in particular CO_2, have a two-third share or more in all regions except Latin America and Africa (and East Asia), where deforestation and savanna burning contribute about one-third, of which CO_2 contributes four-fifth.
- Shares of agricultural emissions, predominantly CH_4, contribute about 20%, the highest in the less developed regions, except for the India region where they contribute about 50%; in industrialised regions their share is 5 to 10%.
- At 10% non-sustainable production, biofuels are calculated to contribute about 5% in the regions Africa and India.
- Similar shares of about 5% originate in industrial processes in Europe, the Middle East and East Asia and waste CH_4 in OECD regions.

5.2. *Validation*

In comparing our CO_2 emission estimates with the IPCC (1992) inventory for 1990, we arrive at the global picture shown in Table 13.

In conclusion, there is good agreement for fossil fuel

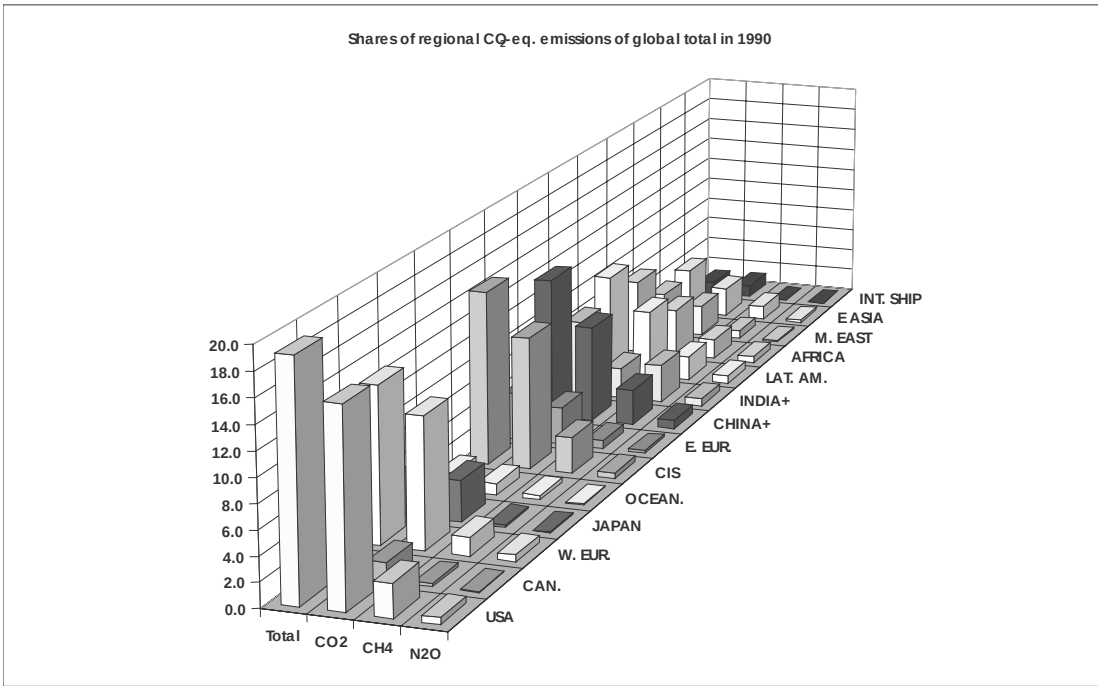

Fig. 3. Contribution (%) of CO_2, CH_4 and N_2O to global CO_2-eq. emissions in 1990 per source and region (GEIA/EDGAR V2.0).

use and cement production. This is also the case when we compare these emissions with the inventory prepared by Marland et al. (1994), based on energy statistics compiled by the United Nations. In the latter comparison the largest differences occurred mainly in the group of low emitting countries (Marland et al., 1999). Biomass burning emissions, although low, also fall within the uncertainty range estimated by IPCC; biofuel emissions, however, are shown to be substantially lower than estimates by the IPCC as part of their biomass burning figure. This difference may be partially caused by our assumption, for reporting purposes, of 10% non-sustainable use.

To compare our CH_4 emission estimates with the IPCC (1992) inventory for 1990, the emission source categories were rearranged to yield the information given in Table 14.

All categories fall well within the uncertainty range estimated by IPCC. Differences for energy production and use might be explained by the relatively high global default emission factor for coal mining proposed by Smith and Sloss (1992). Also the high uncertainties for natural gas losses in the former USSR's massive production area, West Siberia, might give rise to differences in the emission estimates. Differences for biomass burning might be explained by the large uncertainties in the activity estimates of large-scale biomass burning. Different emission factors have also been used.

Comparing our anthropogenic N_2O emission estimates with the IPCC (1992) inventory for 1990 results in Table 15.

From this comparison it can be concluded that, given the high degree of uncertainty of these N_2O emissions, our estimates per source category compare fairly well with the global totals estimated by IPCC. Emissions from arable lands (due to fertiliser use) also fall within the uncertainty range of IPCC, although the IPCC estimate includes the fertiliser-induced N_2O emission only. Emissions from animal excreta were not recognised by IPCC (1992); they have been included in the second assessment on the basis of this study. For a more extensive validation we refer to Bouwman et al. (1995).

A similar comparison has been made for the other gases, showing good agreement on the global scale.

5.3. Limitations and uncertainties

Comparison of the global totals of EDGAR with IPCC best 'middle' estimates and uncertainty ranges for global total emissions provided by IPCC have shown that our estimates in Version 2.0 are generally well in line with 'best estimates' of IPCC, and certainly within the uncertainty ranges. Except for N_2O, further validation of EDGAR results, either in comparison with other inventories or in more regional detail, has not been done. Though it is important to know the accuracy of the estimates, Version 2.0 does not include fully assessed uncertainty estimates, since these are

Table 12
Contribution (%) of CO_2-eq. emissions of regional sources/gases to global total greenhouse gas emissions in 1990

	Global total	Annex I			Non-Annex I		
		total	OECD ('90)	rest Annex I[b]	total	China +	India +
Total anthropogenic sources	100.0	58.7	40.0	18.7	41.3	12.0	6.5
CO_2	74.1	47.9	33.6	14.3	26.3	8.2	2.6
CH_4	21.0	8.9	5.1	3.8	12.1	3.1	3.3
N_2O	4.9	1.9	1.3	0.6	2.9	0.8	0.6
Fossil fuel: combustion	66.2	47.1	33.1	14.0	19.1	7.7	2.1
CO_2	65.7	46.8	32.9	13.9	18.9	7.5	2.1
CH_4	0.3	0.2	0.1	0.1	0.1	0.1	0.0
N_2O	0.3	0.2	0.2	0.0	0.0	0.0	0.0
Fossil fuel: production/transm.	6.7	4.5	2.1	2.5	2.1	0.7	0.1
CO_2	0.8	0.2	0.1	0.1	0.6	0.0	0.0
CH_4	5.8	4.3	1.9	2.4	1.5	0.6	0.1
N_2O	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Biofuel[a]	1.2	0.1	0.1	0.0	1.1	0.2	0.3
CO_2[a]	0.2	0.0	0.0	0.0	0.1	0.0	0.0
CH_4	0.9	0.2	0.0	0.0	0.0	0.2	0.3
N_2O	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Industrial processes	2.5	1.4	1.0	0.5	1.1	0.4	0.1
CO_2	1.8	0.9	0.6	0.3	0.9	0.4	0.1
CH_4	0.1	0.0	0.0	0.0	0.0	0.0	0.0
N_2O	0.7	0.5	0.4	0.1	0.2	0.1	0.0
Agriculture	13.9	4.0	2.5	1.5	9.9	2.5	3.3
CO_2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CH_4	10.8	2.8	1.8	1.0	8.0	1.9	2.8
N_2O	3.2	1.2	0.8	0.4	1.9	0.6	0.5
Biomass burning	7.2	0.0	0.0	0.0	7.2	0.3	0.5
CO_2	5.7	0.0	0.0	0.0	5.7	0.3	0.4
CH_4	0.8	0.0	0.0	0.0	0.8	0.0	0.0
N_2O	0.7	0.0	0.0	0.0	0.7	0.0	0.0
Waste	2.3	1.6	1.3	0.3	0.8	0.2	0.1
CO_2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CH_4	2.3	1.6	1.3	0.3	0.8	0.2	0.1
N_2O	0.0	0.0	0.0	0.0	0.0	0.0	0.0

[a] CO_2 from biofuels estimated at 10% unsustainable production. Thus, this share could in case of 100% unsustainable use be 10 times as high.
[b] Economies in transition in Eastern Europe and the former SU.

often very difficult to deduce. Nevertheless, an indication of the overall uncertainty per compound and per major source is provided in Table 16. Here, at least the order of magnitude of the uncertainties at the regional level is given. Uncertainty assessments can be made at different levels:

- Spatial: for global, regional or country totals or, alternatively, at the grid-cell level.
- Source: for all major or detailed sources.

In both cases one should analyse the intrinsic uncertainty in activity levels, emission factors and grid maps used to allocate per-country emissions to the $1° \times 1°$ grid.

For fossil fuel use and industrial and agricultural production, often reasonably accurate international statistics are available. This means that regional or glo-

Table 13
Comparison of global CO_2 emissions

Source	EDGAR (Pg CO_2-C)	IPCC (Pg CO_2-C)
Energy (fossil)	5.9	6.0 (5.5–6.5)
Cement	0.2	0.2
Biomass burning	0.7[a]	1.6[a] (0.6–2.6)
Global total	6.8	7.8

[a] Including 0.15 and 0.9 Pg C for biofuels for EDGAR and IPCC, respectively.

bal totals are often precise. However, it is known that international statistics, on which EDGAR relies heavily, may show substantial differences in some cases to figures taken from the national statistics of certain countries (Schipper et al., 1992). Less commercial or non-commercial activities such as biofuel use, waste burning and landfilling are, from the viewpoint of traditional economics, less well-known. The same applies to most natural sources, which are spatially so scattered that often no accurate estimates of totals exist. Emission factors show a substantial variation according to the type of process. An exception is formed by factors strongly related to the physical or chemical characteristics of the process, e.g. fuel composition (CO_2, SO_2). For the EDGAR database we have, wherever possible, estimated average regional emission factors for aggregate source types.

For estimating uncertainty of emissions per grid cell, three aspects of the maps are important to consider: (a) the accuracy of the relative intensities (per country); (b) the selection of the theme of the map; (c) the way in which border cells are treated in country-to-grid conversions. It can be concluded from this analysis and the data in Table 16 that the uncertainty estimates for emissions differ substantially depending on the cross-section made in space, sources and compounds.

Table 14
Comparison of flobal CH_4 emissions

Source	EDGAR (Tg CH_4)	IPCC (Tg CH_4)
Enteric fermentation and animal waste	93	105 (85–130)
Energy production and use	94	100 (70–120)
Rice cultivation	60	60 (20–150)
Landfills	36	30 (20–70)
Biomass burning	37[a]	40 (20–80)[a]
Domestic sewage	–	25
Global total	320	360

[a] Including 14 and 9 Tg for biofuel use for EDGAR and IPCC, respectively.

6. Policy applications

As mentioned above, EDGAR V2.0, because of its ability to make various cross-sections per source, region and year, has been used as a key reference for compiling default, globally aggregated, non-CO_2 emission factors for fuel combustion for the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 1996).

Using EDGAR's possibilities to make different cross-sections, we can also draw conclusions on what the largest contributors of greenhouse gas emissions are, where they are and what the fastest growing sources are. This can be done using the overview in Tables 9–12 where regional and sectoral emissions are presented per compound or expressed as CO_2-eq. By comparing activity intensities and emission factors regionally or in time, we can draw conclusions as to what emission sources in what region can be controlled most efficiently. We should stress, however, that a sectoral database like EDGAR can identify in which sectors and regions a percentage-wise emission reduction will have the largest effect on global total and regional emissions, but not whether or not these reductions will be technically, economically or politically feasible.

Another possibility is to use these inventories, consistent across countries, sources and compounds, as a reference data set to compare official national inventories, checking as part of a validation process for completeness, consistency and comparability. This was done for the first National Communications. This application was concluded to be indeed useful for that purpose as it flagged, for instance, a number of source categories for which some countries either did not seem to provide emissions or did not allocate them properly (see Van Amstel et al., 1999). On the other hand, it may also flag possible discrepancies and a number of weaknesses in the present EDGAR Version 2.0 data sets, which will assist in improving the science-based global inventories.

Table 15
Comparison of global N_2 emissions

Source	EDGAR (Tg N)	IPCC (Tg N)
Fossil fuels	0.2	0.4 (0.3–0.9)
Biofuels	0.1	0.1
Adipic acid	0.3	0.5 (0.4–0.6)
Nitric acid	0.2	0.2 (0.1–0.3)
Arable lands	1.0	2.2 (0.03–3.0) [a]
Animal excreta	1.0	– (–)
Biomass burning	0.2	0.5 (0.2–1.0)
Post-burning effects	0.4	– (–)
Global total	3.2	3.9

[a] Including a background emission of about 0.9.

Table 16
Indication of uncertainty ranges in activity levels, emission factors and resulting overall global and regional emissions. S = ±10%, M = ±50%, L = ±100%, V = > 100% and – means not applicable. Sources: general: IPCC (1992, 1994); SEI (Subak et al., 1992); EPA (Ahuja, 1990); World Bank (Ebert and Karmali, 1992) and own estimates based on expert judgement. For CO_2: Marland and Rotty (1984) and Von Hippel et al. (1993)

Main source	Sub-category	Activity data	Emission factors			Total emissions		
			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	–
Biofuel	biofuel combustion	L	S	M	L	L	L	L
Industry/solvent use	iron and 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	–	–	–	–	–	–
Natural sources	natural soils	M	–	L	L	–	L	L
	grasslands	M	–	M	L	–	M	L
	natural vegetation	M	–	M	–	–	M	–
	oceans/wetlands	M	–	L	L	–	L	L
	lightning	S	–	–	–	–	–	–
All sources		–	–	–	–	S	M	L

Quite another application is to use the features of the EDGAR system to link policy at the national level with science at the gridded level by importing official national emissions per source category into EDGAR and converting these to the $1° \times 1°$ grid. This gridded data set, if necessary backed up with EDGAR data for countries or sources for which no official figures are available, can then be used for independent validation by inverse calculations of atmospheric models. However, sufficient atmospheric concentration measurements must be available to produce accurate results. This way of linking the aggregate of official national inventories with scientific budget considerations also forms the ultimate method for checking that these inventories, though possibly comparable within the group, do not contain a substantial bias.

7. Conclusions

We have compiled global inventories of greenhouse gas emissions by country and by source category including conversion to the $1° \times 1°$ grid. A partial validation by comparing our estimates per major source with global total estimates of *the Intergovernmental Panel on Climate Change* (IPCC) has generally shown good agreement. Also comparisons with nationally compiled inventories showed reasonable agreement. In addition, comparing our fossil fuel CO_2 inventory with the one based on UN statistics showed interesting features of both data sets.

We have illustrated some of the powerful applications possible with the data sets that have now been compiled. A special effort has been made to compile a global inventory of emissions from fossil fuel production and biofuel use, since these are significant sources of emissions of methane and carbon monoxide, respectively, on a global level. Furthermore, they also form major sources in some regions such as fossil fuel production in the former USSR and USA and biofuel use in India and China. Information extracted from the database is provided for external users in a standard format through Internet (anonymous FTP server: info.rivm.nl, sub-directory: /pub/lae/EDGARV20),

Table 17
Calculated aggregated emission factors for CO, NO_x, NMVOC and SO_2 from fossil fuel combustion in 1990 (g GJ^{-1}, full molecular mass, rounded off) (EDGAR V2.0). Industry; excluding the energy sector, power generation; including autoproducers and cogeneration, total other sector; residential, commercial, other/non-specified, non-road surface transport; rail, inland water, other/non-specified

Fuel type/	Main sector	Global average	OECD					Econ. in transition		Other non-OECD regions					
Compound			USA	Can.	Western Europe	Japan	Oceania	CIS	E. Europe	Latin Am.	Africa	Middle East	India region	China region	East Asia
Gas: *CO*															
Solid	industry	140	80	150	130	150	150	150	120	150	150	130	150	150	150
Solid	power generation	15	15	15	15	20	20	20	20	20	20	10	20	20	20
Solid	total other sector	4700	5000	5700	3000	2800	4800	5000	3800	5600	4900	6000	4500	5000	5000
Solid	non-road surface transport	150			100		150	150	100	150	150	100	150	150	
Liquid	industry	10	20	10	10	10	10	10	10	10	10	10	10	10	10
Liquid	power generation	15	20	10	10	10	10	20	10	10	10	10	10	10	10
Liquid	total other sector	30	20	30	30	40	170	20	20	20	40	30	60	30	40
Gasoline	road transport	6200	4700	4700	6300	2900	5300	9800	10700	8400	8200	8500	11100	8500	9400
Diesel	road transport	900	600	600	600	1100	900	1300	900	1200	1000	1100	1000	1100	1300
LPG	road transport	2500	2400	2400	2800	2400	2400			2400					2400
Liquid	non-road surface transport	800	600	500	600	800	700	700	800	1100	1000	1100	900	900	1100
Gas	industry	30	40	20	40	20	20	20	20	20	20	20	20	20	20
Gas	power generation	20	20	20	10	20	20	20	10	20	20	20	20	20	20
Gas	total other sector				550				70						
Gas: NO_x															
Solid	industry	270	560	190	300	180	250	270	310	180	240	180	250	240	200
Solid	power generation	310	350	310	200	390	340	330	140	370	390	300	380	390	360
Solid	total other sector	80	80	80	80	90	80	80	60	80	80	70	80	80	80
Solid	non-road surface transport	270			190		270	270	180	270	270	180	270	270	
Liquid	industry	60	60	60	70	40	70	60	100	60	70	50	60	50	60
Liquid	power generation	200	170	240	230	120	100	260	190	230	180	150	200	220	220
Liquid	total other sector	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Gasoline	road transport	600	700	700	700	200	700	500	500	500	700	500	300	500	400
Diesel	road transport	800	700	700	700	800	700	900	1000	900	1000	900	900	900	900
LPG	road transport	900	900	900	900	900	900			900					900
Liquid	non-road surface transport	700	600	600	700	700	600	600	1000	900	900	900	900	700	800
Gas	industry	160	270	110	150	110	110	110	130	110	110	110	110	110	110
Gas	power generation	160	200	150	150	150	150	150	190	150	150	150	150	150	150
Gas	total other sector	60	50	50	80	50	50	50	60	50	50	50	50	50	50
Gas	non-road surface transport														

(continued on next page)

Table 17 (*continued*)

Fuel type/ Compound	Main sector	Global average	OECD					Econ. in transition		Other non-OECD regions					
			USA	Can.	Western Europe	Japan	Oceania	CIS	E. Europe	Latin Am.	Africa	Middle East	India region	China region	East Asia
Fuel type	Main sector	Global average	OECD					Former Centr. Pl. Europe		Other non-OECD regions					
			USA	Can.	Western Europe	Japan	Oceania	CIS	E. Europe	Latin Am.	Africa	Middle East	India region	China region	East Asia
Gas: *NMVOC*															
Solid	industry	20	10	20	20	20	20	20	15	20	20	20	20	20	20
Solid	power generation	2	2	1	2	2	1	1	3	2	2	1	2	2	2
Solid	total other sector	180	200	200	80	80	170	200	130	200	200	190	170	200	200
Solid	non-road surface transport	20			14		20	20	13	20	20	13	20	20	
Liquid	industry	2	4	2	2	1	2	2	2	2	2	2	2	2	2
Liquid	power generation	3	5	3	3	2	2	3	5	3	3	2	3	3	3
Liquid	total other sector	3	3	3	3	3	3	3	2	3	3	3	3	3	3
Gasoline	road transport	1000	600	1000	1300	1400	1100	1100	1700	1300	1300	1300	4300	1200	3000
Diesel	road transport	170	180	110	140	150	130	220	190	190	200	190	160	210	190
LPG	road transport	380	370	370	400	370	370			370					370
Liquid	non-road surface transport	140	160	80	120	110	100	110	180	170	190	180	150	160	170
Gas	industry		10		5				5						
Gas	power generation				5				5						
Gas	total other sector				35				10						
Gas	non-road surface transport														
Gas: SO_2															
Solid	industry	1100	800	120	770	250	500	940	1700	190	740	380	1750	5600	300
Solid	power generation	900	800	1400	900	500	500	900	1500	800	700	1500	600	1000	1000
Solid	total other sector	900	700	1100	900	500	800	800	900	1000	600	1400	600	1000	700
Solid	non-road surface transport	900			700		400	800	800	600	700	1100	500	1000	
Liquid	industry	410	160	380	340	80	210	630	660	650	690	700	740	540	530
Liquid	power generation	900	500	1100	1000	50	400	1200	1500	1100	900	700	1000	1000	1100
Liquid	total other sector	180	220	160	150	100	130	140	380	200	150	280	180	190	200
Gasoline	road transport	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Diesel	road transport	170	140	140	140	200	140	140	140	140	140	140	540	250	140
LPG	road transport	20	20	20	20	20	20			20					20
Liquid	non-road surface transport	160	130	110	130	220	150	80	130	130	140	140	520	200	130
Gas	industry	20	25	5	80	30	5		5	5	10	5		40	
Gas	power generation		10	0	60	5			15	1		0		35	
Gas	total other sector		10	0	60	5			15	1		0		35	
Gas	non-road surface transport				140										

providing gridded emissions per compound and per sector as well as regional summary tables per compound for 1990.

The database will be maintained and updated. Version 3.0 will include emissions extending to 1995 and a time series going back to 1970. It will include an ammonia inventory and a compilation of time profiles, seasonal (i.e. monthly) variation.

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Appendix A

Calculated globally and regionally aggregated emission factors for CO, NO_x, NMVOC and SO_2 from fossil fuel combustion in 1990 (rounded off; in g GJ^{-1}, full molecular mass) (EDGAR V2.0) are shown in Table 17.

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Global air emission inventories for anthropogenic sources of NO_x, NH_3 and N_2O in 1990

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Abstract

Global emission inventories with 1°×1° resolution were compiled for nitrogen oxides (NO + NO_2, together denoted as NO_x), ammonia (NH_3) and nitrous oxide (N_2O) emissions. For NO_x the estimated global anthropogenic emission for 1990 is about 31 million ton N $year^{-1}$. The major anthropogenic sources identified include fossil fuel combustion (70%, of which the major sources are road transport and power plants) and biomass burning (20%). Natural sources contribute about 19 million ton N $year^{-1}$, mainly lightning and soil processes. For NH_3 the estimated global emission for 1990 is about 54 million ton N $year^{-1}$. The major sources identified include excreta from domestic animals and wild animals, use of synthetic N fertilisers, oceans and biomass burning. About half of the global emission comes from Asia, and about 70% is related to food production. For N_2O the major sources considered include fertilised arable land, animal excreta, soils under natural vegetation, oceans, and biomass burning. The global source of N_2O is about 15 million ton N_2O–N $year^{-1}$ of which about 30% is related to food production. All three inventories are available on a sectoral basis on a 1°×1° grid for input to global atmospheric models and on a regional/country basis for policy analysis.

Keywords: Ammonia; emission; global inventory; nitrogen oxides; nitrous oxide; policy options; uncertainty

Introduction

Industrial, agricultural and other anthropogenic activities have modified global biogeochemical nitrogen (N) cycles. Humans have doubled the natural rate of N fixation (Vitousek et al., 1997), which is reflected by increasing emissions of many trace gases and particulate matter into the atmosphere. Three important N substances that are emitted by human activities are nitric oxide and nitrogen dioxide (NO and NO_2, respectively, together denoted as NO_x), ammonia (NH_3) and nitrous oxide (N_2O). Many different sources are responsible for the emission of N gases. Fossil fuel combustion, biomass burning, lightning and microbiological emissions from both natural and agricultural soils are the major processes involved in the production of NO_x and N_2O while NH_3 stems from a large number of sources, including volatilisation from animal waste and synthetic fertilisers, biomass burning, losses from soils under natural vegetation, agricultural crops, emissions from human excreta and waste, industrial processes and fossil fuel combustion (Olivier et al., 1996; Lee et al., 1997; Bouwman et al., 1997).

Once in the troposphere, NO_x and NH_3 are involved in several chemical reactions. Gases and the products of chemical reactions are transported in the atmosphere and deposited elsewhere. NO_x is a short-lived gas with a lifetime of 1–10 days. NO_x contributes to acidification and to the generation of ozone (O_3) in the troposphere, thus affecting the oxidant balance of the troposphere and

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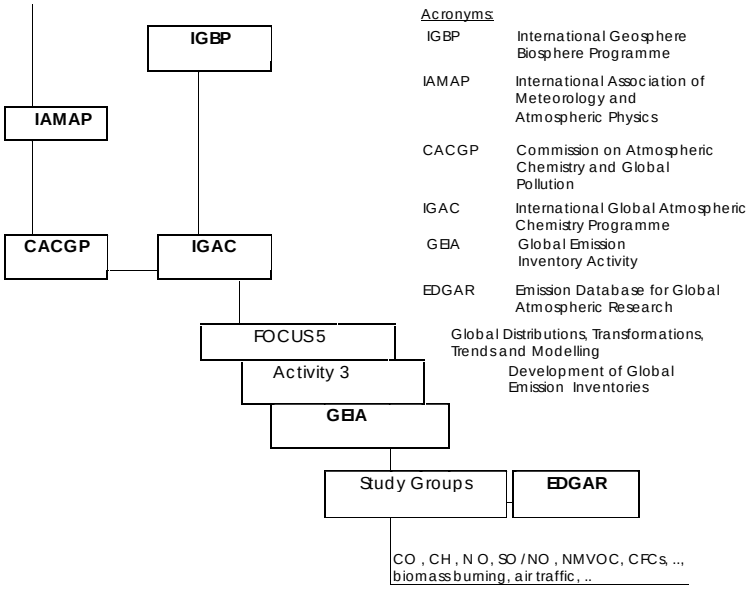


Fig. 1. Scheme representing the relation between the various initiatives and programmes involved in the development of global emission inventories.

affecting human health because of its toxicity. Furthermore, NO_x is of concern because of its effects on human health, vegetation and materials.

Ammonia has a lifetime of only a few hours to a few days. It is the primary acid-neutralising agent in the atmosphere, where it influences the pH of aerosols, cloud water and rainfall. Ammonia may also contribute to acidification, as 1 mol of ammonium sulphate, $(NH_4)_2SO_4$, can result in the release of 4 mol of acidity by nitrification. Dry deposition of NH_3 can also result in the release of one proton by nitrification. Finally, concern has been expressed over the eutrophication of ecosystems and soil acidification caused by enhanced rates of atmospheric deposition of NH_3 and NO_x.

Nitrous oxide is a greenhouse gas, being chemically inert in the troposphere with a long lifetime (~120 years). Its radiative forcing is about 300 times that of CO_2. Part of the N_2O is destroyed in the stratosphere forming NO, one of the species contributing to ozone depletion.

In the International Global Atmospheric Chemistry Programme (IGAC) and other core projects of the International Geosphere-Biosphere Programme (IGBP) the environmental impacts of the different gas species are studied. Within IGAC, the Global Emissions Inventory Activity (GEIA) is a platform for collaboration of international experts in the development of global emission inventories (Fig. 1) with a spatial resolution of 1×1°. These inventories have been made available to the research community and policy makers (Graedel et al., 1993; Graedel et al., 1995).

In the framework of GEIA, the Netherlands Organisation for Applied Scientific Research (TNO), and the National Institute of Public Health and the Environment (RIVM) have committed themselves to co-ordinating inventories of anthropogenic NMVOC and anthropogenic and natural emissions of N_2O and NH_3. In addition, TNO and RIVM have jointly developed the Emission Database for Global Atmospheric Research (EDGAR), a database and software tool to provide estimates on a sectoral basis of annual global air emissions of (i) direct greenhouse gases (carbon dioxide, CO_2; methane, CH_4; nitrous oxide, N_2O); (ii) gases that affect ozone chemistry (carbon monoxide, CO; NO_x; and non-methane volatile organic compounds, NMVOC); (iii) gases involved in aerosol chemistry and acidification (SO_2 and NH_3); and (iv) compounds involved in stratospheric ozone depletion (such as CFCs and halons).

Because it aims at supporting both policy development and atmospheric research, EDGAR includes data sets covering all major anthropogenic and most natural sources of greenhouse gases for 1990, both per country and on a 1×1° resolution. EDGAR is a comprehensive database, and it has a complete and consistent geographic coverage of sources, sectors and compounds. Currently, the major difference between inventories of EDGAR and of GEIA is that GEIA inventories provide the best global gridded inventories available to date for specific compounds, but they often lack sectoral details. The sectoral and country details provided by the EDGAR database are a major advantage for policy applications (often aimed at specific sectors) and modellers (often requiring additional sector-specific assumptions such as seasonal variation or stack height). In the case of NH_3 and N_2O the GEIA and EDGAR inventories are identical, and for anthropogenic NO_x the

EDGAR inventory acts as default for the GEIA 1990 inventory. The EDGAR inventories are available (by sector on grid and per region) for external users through anonymous FTP at ftp://info.rivm.nl/pub/lae/EDGARV20/. All GEIA inventories are described in journal papers and are available for the research community and for policy makers through the GEIA web site at http://blueskies.sprl.umich.edu/geia/.

The focus of this paper is on the anthropogenic sources on NO_x, NH_3 and N_2O. Firstly, the underlying framework of EDGAR for developing country, regional and grid-based emissions will be summarised to illustrate that the inventories are based on identical grouping of countries, sectors and processes, using the same sources of data. As such they are consistent and intercomparable. For the natural sources of the three gases, mainly soils under natural vegetation and oceans the reader is referred to Bouwman et al. (1995, 1997) for detailed descriptions of inventories of N_2O and NH_3 and to Yienger and Levy (1995), Davidson and Kingerlee (1997) and Price et al. (1997) for NO_x. Secondly, the resulting inventories of annual anthropogenic emissions of NO_x, NH_3 and N_2O will be discussed. Subsequently, the uncertainties in annual emission estimates, applications of the emission inventories, and policy options for reducing emissions will be discussed. Finally, a number of recommendations for improvement of the inventories will be given.

Underlying framework for calculating emissions

The EDGAR database system calculates emissions of the different gases on the basis of activity data, emission factors and other explanatory variables. The underlying information is organised by source category, by country or region or as gridded maps, and for a number of sources by season as well. The following source groups are available in the system: (i) energy production and combustion (by sector and fuel type; including road traffic and stationary combustion); (ii) biofuel use (e.g. fuelwood); (iii) industrial production (for several products); (iv) agriculture (animal breeding, fertiliser use, rice production); (v) biomass burning (deforestation and savanna burning); (vi) waste treatment (landfills, waste burning); (vii) natural sources (soils, vegetation, oceans, wetlands, lightning). Details on the structural design of the design of the EDGAR system can be found in Olivier et al. (1994, 1996).

Activity data in EDGAR are from international statistics, such as IEA (1994) (commercial energy data), UN (1995) (industrial production), and FAO (1991, 1995) (agricultural data), because all these data are mostly collected at the country level and stored in the same format, which is most efficient for data processing. For biofuel use, for which no complete statistics exist, we developed a global data set, based on estimates of total biomass use per country by Hall et al. (1994), except for some industrialised countries, where IEA statistics were used, and for countries in the Middle East where Veldt (1992) and Leach (1988) were used. This data set resulted in a global consumption estimate of 50 EJ for 1990, which is considerably higher than the FAO estimates.

Emission factors are either defined uniformly for all countries or for individual countries or for groups of countries. In the latter case we distinguished OECD countries, Eastern Europe and former USSR, and other non-OECD countries. In some cases, such as for road traffic, we used emission estimates for individual countries and independently defined activity levels to derive country specific emission factors (Samaras, 1993). The inventories for ammonia (NH_3) and nitrous oxide (N_2O) were developed with a very detailed analysis of their emission sources, using the most detailed activity data and emissions factors and an extensive evaluation of existing literature. Bouwman et al. (1995; 1997) provide all details on these inventories. The inventory of nitrogen oxide (NO_x) was based on a compilation of emission factors for stationary energy combustion and industrial sources for European countries collected by TNO-MW (1990) for its LOTOS database, developed primarily for tropospheric ozone modelling, and extrapolated to other countries.

When available, major point sources are used to distribute emissions. If the allocation of point sources is not relevant or not known, thematic maps on $1\times1°$ grid were used as allocation functions to convert country emissions to gridded emissions. For fuel combustion in industry and electric power generation, we used point source information and area source data from the LOTOS database (TNO-MW, 1990) and EPA (1994) to distribute country totals for Europe and the USA, respectively. For the other regions population density was used as a surrogate allocation function. The same approach was used for some industrial sources. A population density map was used as a default when no source-specific map was available, or when point source data were available for a few countries only. The population map used is the Harvard map (Logan, pers. comm., 1993) based on the country-to-grid cell conversion defined for 186 countries by Lerner et al. (1988). Details on the emission factors and grid maps used for the spatial distribution for the various source categories distinguished can be found in Olivier et al. (1996), Bouwman et al. (1995) and Bouwman et al. (1997) for the NO_x, N_2O and NH_3 inventories, respectively.

Emission inventories for NO_x, NH_3 and N_2O

Table 1 presents the global estimates of the different sources of atmospheric emissions of NO_x, NH_3 and N_2O in 1990, including an uncertainty range. The

Table 1

Global sources of atmospheric NO_x, NH_3 and N_2O in 1990 and their uncertainty ranges (Tg N $year^{-1}$; 1 Tg = 10^{12} g). Uncertainties of totals are calculated as the sum of the ranges for individual sources (absolute uncertainty ranges).

Source	NO_x[a]		NH_3[b]		N_2O[c]	
	Emission	Uncertainty	Emission	Uncertainty	Emission	Uncertainty
Anthropogenic sources						
Fossil fuel combustion (surface)	21.3	13–31	0.1	0.0–0.2	0.2	0.1–0.5
Aircraft	0.6	–[d]	–	–	–[d]	–[d]
Industrial processes	1.5	–[d]	0.2	0.1–0.3	0.3	0.1–0.5
Animal excreta	–	–	21.6	10–30	1.0	0–2
– Nondairy cattle			8.6		0.4	
– Dairy cattle			4.3		0.2	
– Pigs			3.4		0.1	
– Other animals			5.3		0.3	
Synthetic fertiliser use on arable land	–[e]	–	9.0	4.5–13.5	1.0	0.3–2.3
Crops and crop decomposition	–[e]	–	3.6	1.4–5	–	–
Biomass burning	7.7	3–15	5.9	3.0–7.7	0.7	0.4–1.0
– Savanna burning	2.9		1.8		0.1	
– Deforestation	1.1		1.4		0.4[f]	
– Agricultural waste	2.2		0.5		0.1	
– Biofuels	1.6		2.2		0.1	
Human excreta and pets	–	–	2.6	1.3–3.9	–	–
Sewage treatment	–	–	–	–	–	–
Coastal waters	–	–	–	–	–	–
Total anthropogenic	31.1	16–46	43.0	20–61	3.2	0.9–6.3
Natural sources						
Soil microbial production	5.5[g]	4–12	2.4	0–10	5.2[i]	2.6–7.8
Grasslands	–[e]	–	–	–	1.4	0.7–2.1
Background emissions arable land	–[e]	–	–	–	0.9	0.4–1.4
Oceans	–	–	8.2	3–16	3.6	2.8–5.7
Lightning	12.2[h]	2–20	–	–	–	–
Excreta of wild animals	–	–	0.1	0–1	–	–
Atmospheric NH_3 oxidation to NO_x	0.9	0–1.6	–	–	–	–
Stratospheric destruction of N_2O	0.7	0.4–1	–	–	–	–
Atmospheric NH_3 oxidation to N_2O	–	–	–	–	0.6	0.3–1.2
Total natural	19.3	6–35	10.7	3–27	11.7	6.8–18.2
Total anthr. + natural	50.4	22–81	53.7	23–88	14.9	7.7–24.5

– indicates no data available or not identified as a source.
[a] EDGAR inventory; Olivier et al. (1996).
[b] GEIA/EDGAR inventory; Bouwman et al. (1997).
[c] GEIA/EDGAR inventory; Bouwman et al. (1995). An updated estimate, in particular of direct and indirect agricultural sources, can be found in Mosier et al. (1998).
[d] Included in fossil fuel combustion.
[e] Included in soils under natural vegetation.
[f] Including post-burn effects.
[g] Yienger and Levy (1995), current GEIA inventory for soils under natural vegetation, grasslands and fertilised arable lands, including canopy reabsorption. Recently, Davidson and Kingerlee (1997) presented revisions of the estimates of Yienger and Levy (1995) based on recent measurements and a more sophisticated stratification of ecosystems. The global estimate of Davidson and Kingerlee (1997) is 13 Tg NO_x–N $year^{-1}$, accounting for canopy reabsorption. This recent update is included in Fig. 2a.
[h] Price et al. (1997), GEIA inventory.
[i] Adapted from Kreileman and Bouwman (1994).

uncertainties are discussed in more detail below. For each compound there are three or four major source categories, often with uncertainties of 50% or more. Since the estimates for different sources can be considered as being independent, the uncertainty in the global total budget is not the sum of all uncertainties, but it has a similar value. Tables 2–4 show the emissions by region for NO_x, NH_3 and N_2O, respectively, for the various anthropogenic sources The results of the three inventories will be briefly discussed, and a comparison with literature data is made.

NO_x inventory

For NO_x the estimated global anthropogenic emission for 1990 is 31 million ton NO_x–N year^{-1}, which is about 60% of the total global emissions of 50 million ton NO_x–N year^{-1} (Table 1). The major anthropogenic sources are fossil fuel combustion (70%, of which road transport 31% and power plants 20% of global total), biomass burning (20%), industrial processes (5%) and biofuel use (5%) (Table 1). Hence, regions with either a high energy consumption, such as the USA, OECD Europe and the former USSR, or regions where large amounts of biomass are burnt, such as Africa, Latin America or China, are major contributors (Table 2). About 25% of the global total emissions stem from North America, while Western Europe, the former USSR, Latin America, Africa and China each contribute about 10%. Figure 2a shows the distribution of the total NO_x emissions from anthropogenic and natural sources on a 1×1° grid.

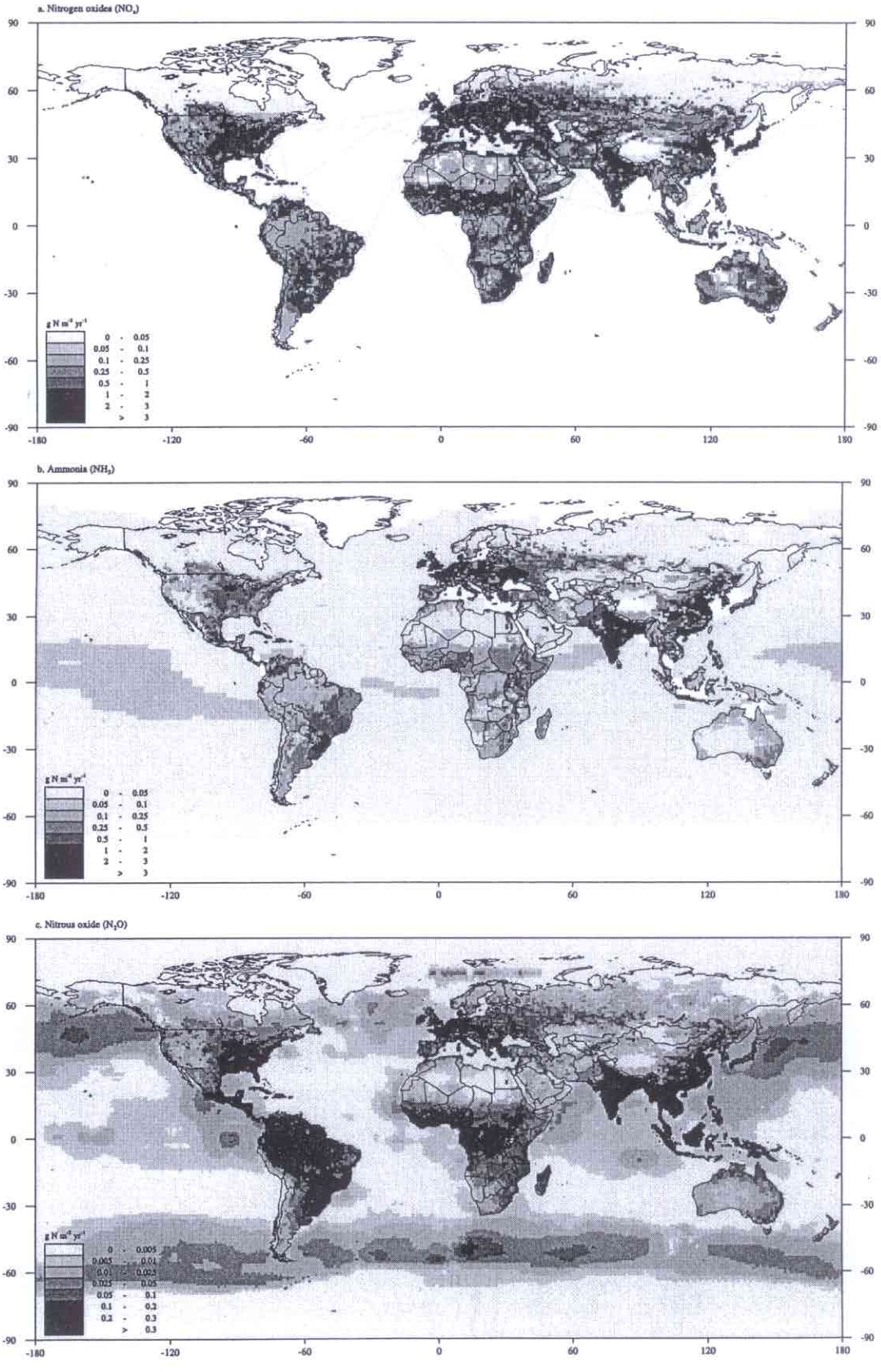
Globally, our results for NO_x are consistent with the IPCC estimates (Prather et al., 1995) for energy use and biomass burning. There are, however, differences in

Table 2

Global estimates of anthropogenic NO_x emissions in 1990 (Gg NO_x–N year^{-1}; 1 Gg = 10^9 g)

Source/subsector	Total	Can.	USA	Lat. Am.	Africa	W. Eur.	E. Eur.	f.S.U.[a]	M.East	India+	China+	E Asia	Ocean.	Japan	Int. ship
Total	31099	582	7324	2750	3727	4009	740	3312	971	1810	3282	1109	416	837	229
Fossil fuel	21912	503	6907	1205	739	3518	614	2863	683	790	2175	613	375	698	229
Industry	3310	47	787	109	73	354	104	594	52	169	821	64	27	110	0
Power generation	6286	93	1961	149	289	665	233	1268	138	308	837	126	137	83	0
Other transformation sector[b]	708	19	153	54	21	129	27	97	47	16	57	30	9	49	0
Residentials[c]	864	20	153	29	14	199	34	164	47	13	133	26	4	30	0
Road transport	9593	299	3557	825	325	2039	205	564	368	261	258	332	182	377	0
Non-road land transport	342	12	54	12	2	35	5	105	1	17	56	10	6	26	0
Air transp. (domestic + intern.)	579	14	241	26	15	97	5	71	30	8	14	24	11	24	0
International shipping	229	0	0	0	0	0	0	0	0	0	0	0	0	0	229
Biofuel	1554	16	136	79	260	48	7	15	46	345	471	122	9	0	0
Industry	306	15	115	18	17	44	6	14	2	40	15	16	4	0	0
Residentials etc.	1248	1	20	61	243	3	1	1	44	305	457	3	6	0	0
Industrial processes	1467	18	96	96	51	259	75	222	76	58	287	90	10	128	0
Iron and steel	292	1	10	13	2	59	20	68	3	5	46	14	3	48	0
Chemicals[d]	132	6	22	6	2	17	10	28	3	3	30	2	0	3	0
Cement	1044	11	65	77	47	183	45	125	70	50	211	75	77	7	0
Landuse/waste treatment	6166	45	185	1370	2677	184	45	213	166	617	348	283	21	11	0
Deforestation	1083	0	0	508	337	0	0	0	0	78	49	111	0	0	0
Savanna burning	2866	0	0	671	2133	0	0	0	0	11	23	27	0	0	0
Agricultural waste burning	2218	45	185	191	207	184	45	213	166	528	276	146	21	11	0

[a]f.S.U. = former Soviet Union.
[b]Other transformation sectors includes refineries, coke ovens, blast furnaces, etc., including fuel combustion for fuel extraction.
[c]Including commercials.
[d]Sum of nitric acid and ammonia production.


a. Nitrogen oxides (NO_x)
g N m^{-2} yr^{-1}
0 - 0.05
0.05 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 1
1 - 2
2 - 3
> 3
b. Ammonia (NH_3)
g N m^{-2} yr^{-1}
0 - 0.05
0.05 - 0.1
0.1 - 0.25
0.25 - 0.5
0.5 - 1
1 - 2
2 - 3
> 3
c. Nitrous oxide (N_2O)
g N m^{-2} yr^{-1}
0 - 0.005
0.005 - 0.01
0.01 - 0.025
0.025 - 0.05
0.05 - 0.1
0.1 - 0.2
0.2 - 0.3
> 0.3
90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180

Opposite page: Fig. 2. Global distribution of emissions of: (a) NO_x, (b) NH_3, and (c) N_2O from all anthropogenic and natural surface sources including oceans. See Table 1 for the various sources included in the inventories. For the NO_x inventory the emissions from soils were derived from Davidson and Kingerlee (1997), which is an update on the basis of recent measurements and a more detailed stratification scheme of the current GEIA inventory of Yienger and Levy (1995). Note that legend classes for N_2O are 10 × as small as for other gases.

regional emission estimates for Asia between EDGAR and e.g. Kato and Akimoto (1992), which can be partly attributed to differences in the assumptions on the amount of biofuel use in different categories and differences in the degree of differentiation in vehicle fleets. Some differences in emission factors and increased fuel consumption in 1990 can explain another part of the disagreement.

NH_3 inventory

For NH_3 the estimated total global emission for 1990 is about 54 million ton NH_3–N $year^{-1}$, of which 43 million ton NH_3–N (about 80%) stems from anthropogenic sources. The major anthropogenic sources identified include excreta from domestic animals (50%, of which non-dairy cattle 25%, dairy cattle 13%, and pigs 10% of the global total), use of synthetic N fertilisers (25%), biomass burning (15%), crops (10%), and human population and pets (8%) (Table 1). About half of the global emission comes from Asia, and about 70% is related to food production. The regions with highest emission rates are located in Europe, the Indian subcontinent, and China, reflecting the patterns of animal densities and type and intensity of synthetic fertiliser use (Table 3). In Latin America, the former USSR, Western and Eastern Europe and Japan animals contribute more than 60% to the regional total. Synthetic fertilisers are large regional sources in Asia contributing 30% or more, with China having the highest percentage of 45%. The overall uncertainty in the global emission estimate is 25% (95% confidence level), while the uncertainty in regional

Table 3
Global estimates of anthropogenic NH_3 emissions in 1990 (Gg NH_3–N $year^{-1}$)

Source/ subsector	Total	Can.	USA	Lat. Am.	Africa	W. Eur.	E. Eur.	f.S.U. [a]	M. East	India+	China+	E Asia	Ocean.	Japan	Int. ship
Total	43039.7	456.0	2897.9	6283.8	5414.9	2878.7	1138.3	3402.6	1168.6	7608.0	8448.6	2180.4	883.4	278.6	0.0
Fossil fuel combustion	88.5	4.8	58.2	0.7	0.2	3.9	2.7	0.4	0.4	1.1	7.0	1.0	0.9	7.0	0.0
- Other transformation sectors [b]	0.0	0.0	0.0	0.0	0.0	0.5	2.6	0.0	0.1	0.9	6.9	0.7	0.0	0.4	0.0
- Road transport	76.5	4.8	58.2	0.7	0.2	3.4	0.2	0.4	0.3	0.3	0.2	0.3	0.9	6.6	0.0
Biofuel	2149.6	24.5	178.9	160.6	397.2	62.3	10.2	22.5	50.1	539.0	474.0	204.3	5.7	0.3	0.0
- Industry	403.6	22.4	141.1	25.7	23.8	57.2	9.2	20.3	2.9	49.6	22.1	23.9	5.2	0.2	0.0
- Other transformation sectors	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.7	0.0	0.0	0.0
- Residentials	1742.4	2.1	37.8	134.9	373.4	5.1	1.0	2.3	47.2	509.4	451.9	176.7	0.5	0.0	0.0
Industrial processes	202.9	7.7	29.9	8.5	4.6	26.2	14.0	37.6	7.3	14.6	42.8	6.1	0.5	3.0	0.0
- Chemicals [c]	202.9	7.7	29.9	8.5	4.6	26.2	14.0	37.6	7.3	14.6	42.8	6.1	0.5	3.0	0.0
Landuse/waste treatment	40598.7	418.9	2630.9	6114.0	5012.9	2786.2	1111.4	3342.0	1110.8	7033.3	7924.8	1968.9	876.3	268.3	0.0
- Synthetic fertilizers	9020.8	92.7	529.3	542.1	194.0	453.6	165.9	461.2	221.2	1992.0	3667.0	621.9	50.9	29.1	0.0
- Crops	3594.4	114.9	473.8	379.7	439.3	226.4	119.4	574.0	168.3	534.3	280.5	148.7	123.6	11.5	0.0
- Domesticated animals	21613.9	177.3	1417.2	3874.5	2624.1	1869.2	739.0	2111.9	604.7	3756.0	3213.5	589.9	475.0	161.8	0.0
- Humans/pets	2648.3	13.3	125.0	224.0	321.0	188.8	61.7	144.7	101.6	585.5	624.1	185.3	11.4	61.8	0.0
- Deforestation	1410.9	0.0	0.0	528.0	336.6	0.0	0.0	0.0	4.7	98.5	93.1	349.3	0.7	0.0	0.0
- Savanna burning	1827.2	0.0	0.0	484.6	1091.7	0.0	0.0	0.0	0.2	9.0	18.3	19.5	203.9	0.0	0.0
- Agricultural waste burning	483.3	20.7	85.6	81.0	6.1	48.3	25.5	50.2	10.1	58.0	28.4	54.3	10.8	4.2	0.0

[a] f.S.U. = former Soviet Union. [b] Other transformation sector refers to coke ovens.
[c] Chemicals refers to total nitrogen fertiliser production.

emissions is much greater. Figure 2b shows the distribution of the total NH_3 emissions from anthropogenic and natural sources on a 1×1° grid.

The global NH_3 emission from all sources resulting from this study is somewhat higher than that presented by Dentener and Crutzen (1994), but much lower than that of Schlesinger and Hartley (1992). The major difference between this study and Schlesinger and Hartley is caused by lower emissions from animal waste and undisturbed ecosystems. Our estimate for emissions from animal waste is similar to that of Dentener and Crutzen (1994). The major differences between our inventory and that of Dentener and Crutzen arise from higher estimates for NH_3 from fertilisers (2.6 million ton higher) and biomass burning (factor 2 higher). For a more comprehensive discussion we refer to Bouwman et al. (1997).

N_2O inventory

The estimated total global N_2O emission is about 15 million ton N_2O–N $year^{-1}$, whereas the total anthropogenic emissions in 1990 are 3.2 million ton N_2O–N (20%), including emissions caused by post-burning effects of deforestation. Most anthropogenic emissions are related to land use and waste treatment, with about 75% of the total stemming from fertiliser use on arable lands (30%), animal excreta (30%) and biomass burning (20%; predominantly from deforestation, including an estimate of post-burning emissions of 0.4 million ton N_2O–N) (Table 1). Industrial processes account for 14% of the anthropogenic emissions and the remainder is mainly related to fuel combustion. Because of the high fraction of emissions from agriculture and other land-use

Table 4
Global estimates of anthropogenic N_2O emissions in 1990 (Gg N_2O–N $year^{-1}$)

Source / subsector	Total	Can.	USA	Lat. Am.	Africa	W. Eur.	E. Eur.	f. S.U.[a]	M. East	India+	China+	E Asia	Ocean.	Japan	Int. Ship
Total	3214.2	50.5	353.7	462.1	357.7	366.2	122.8	294.3	85.1	400.0	501.2	134.7	50.0	34.0	1.9
Fossil fuel	165.9	4.8	60.3	4.5	4.0	20.9	6.9	17.5	3.4	5.2	22.0	3.4	2.4	8.7	1.9
– Industry	31.0	0.4	3.7	1.2	0.9	3.8	0.9	4.5	0.5	1.9	10.0	1.0	0.2	2.0	0.0
– Power generation	49.6	0.8	15.3	0.8	2.0	7.7	3.7	7.0	0.7	2.2	6.1	0.8	1.1	1.3	0.0
– Other transformation sectors[b]	4.9	0.1	1.0	0.3	0.1	1.1	0.8	0.4	0.3	0.1	0.3	0.1	0.1	0.2	0.0
– Residentials etc.	17.5	0.2	1.8	0.6	0.3	3.0	1.1	3.4	1.0	0.3	4.4	0.7	0.1	0.6	0.0
– Road transport	55.8	3.1	37.1	1.5	0.5	4.6	0.4	1.1	0.7	0.4	0.6	0.6	0.8	4.4	0.0
– Non-road land transport	2.1	0.1	0.3	0.1	0.0	0.2	0.0	0.6	0.0	0.1	0.5	0.1	0.0	0.1	0.0
– Air transp. (domestic + intern.)	2.9	0.1	1.2	0.1	0.1	0.5	0.0	0.4	0.2	0.0	0.1	0.1	0.1	0.1	0.0
– International shipping	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9
Biofuel	60.3	0.7	3.9	4.5	11.5	1.5	0.2	0.5	1.5	16.0	13.8	5.9	0.3	0.0	0.0
– Industry	8.6	0.6	2.8	0.5	0.5	1.3	0.2	0.4	0.1	1.0	0.4	0.7	0.1	0.0	0.0
– Residentials etc.	51.6	0.1	1.1	4.0	11.0	0.2	0.0	0.1	1.4	15.1	13.4	5.2	0.1	0.0	0.0
Industrial processes	458.3	20.7	90.2	21.1	5.0	122.5	40.4	58.3	7.5	19.5	48.6	12.4	0.6	11.5	0.0
– Adipic Acid	282.3	14.8	66.7	14.1	0.0	99.7	29.4	29.4	0.0	0.0	14.1	4.7	0.0	9.4	0.0
– Nitric Acid	176.0	5.9	23.5	7.0	5.0	22.9	11.0	28.9	7.5	19.5	34.4	7.6	0.6	2.1	0.0
Landuse/waste treatment[c]	2529.7	24.3	199.2	432.0	337.3	221.3	75.4	218.0	72.7	359.2	416.8	113.0	46.7	13.7	0.0
– Arable land	963.4	14.5	126.8	47.2	26.3	129.8	41.9	109.2	30.8	123.1	257.8	42.0	6.2	7.7	0.0
– Animals	1021.3	8.0	64.7	177.9	137.6	83.7	31.6	99.8	34.8	185.1	129.1	23.8	39.6	5.6	0.0
– Deforestation	35.1	0.0	0.0	16.5	10.9	0.0	0.0	0.0	0.0	2.5	1.6	3.6	0.0	0.0	0.0
– Post-burn effects def.	360.9	0.0	0.0	169.3	112.3	0.0	0.0	0.0	0.1	26.1	16.3	36.9	0.0	0.0	0.0
– Savanna burning	55.6	0.0	0.0	13.0	41.4	0.0	0.0	0.0	0.0	0.2	0.5	0.5	0.0	0.0	0.0
– Agricultural waste burning	93.4	1.9	7.8	8.0	8.7	7.7	1.9	9.0	7.0	22.2	11.6	6.1	0.9	0.5	0.0

[a] f.S.U. = former Soviet Union.
[b] Other transformation sectors includes refineries, coke ovens, blast furnaces, etc., including fuel combustion for fuel extraction.
[c] Arable land: emissions from fertiliser use, excluding background emission of N_2O of about 0.9 Tg N globally; animals: animal waste; biomass burning: sum of deforestation and savanna burning; post-burn effects: delayed emissions related to deforestation.

related sources, it is not surprising that India, Latin America and China have the highest shares in the regional split (Table 4). The second largest group consists of OECD Europe, Africa, USA and the former USSR, each contributing about 10% of anthropogenic N_2O emissions. Other regions have relatively small emissions. Figure 2c shows the distribution of the total N_2O emissions from anthropogenic and natural sources on a 1°×1° grid.

Comparison of our estimates with N_2O estimates reported by Prather et al. (1995) shows a good agreement. For a more extensive validation we refer to Bouwman et al. (1995) and Bouwman and Taylor (1996).

Overall nitrogen emissions

We have combined the three inventories to calculate the aggregate nitrogen emissions for major anthropogenic sources for nine world regions (Fig. 3). Total anthropogenic air emissions of nitrogen gases contribute to N loading of the atmosphere by 31.1, 43.0 and 3.2 million ton N annually, and have a share each of 60%, 80% and 20% in the global total emission (i.e. including natural sources) of NO_x, NH_3 and N_2O, respectively. Of global total anthropogenic nitrogen emissions to the atmosphere, NH_3 accounts for 55%, NO_x for 40% and N_2O for almost 5%. Globally, agriculture is by far the largest source (almost 50%), and stationary and mobile combustion of fossil fuel are the second and third largest sources (both 15%), while biomass burning accounts for another 10%. Regional source profiles differ substantially: in Latin America and Africa large-scale biomass burning accounts for about 30% of the regional total, whereas for Asian countries agriculture contributes about 60%. This is in contrast with OECD regions where agriculture accounts on average for 30%. About

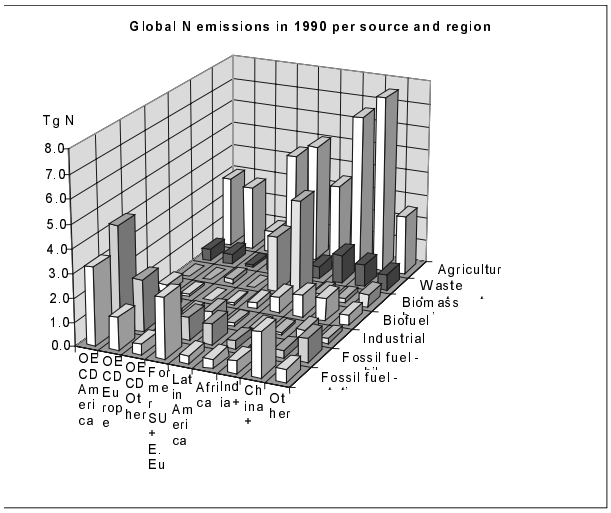


Fig. 3. Anthropogenic emissions of nitrogen gases (NO_x, NH_3 and N_2O) for different world regions presented for major source groups.

50% of global total anthropogenic emissions stem from four sources/regions (Fig. 3), i.e. agriculture in Asia and other developing regions (20% and 10%, respectively), mobile sources in OECD countries (10%), and agriculture in OECD countries (close to 10%). When comparing anthropogenic vs. natural sources of nitrogen, the anthropogenic sources contribute about 2/3 of the global total. The anthropogenic sources of NO_x and NH_3 are much larger than their natural counterparts (Fig. 4), whereas the man-made emissions of N_2O are less than half of the estimated natural emissions. The uncertainties in the estimates are rather large as shown in Fig. 4.

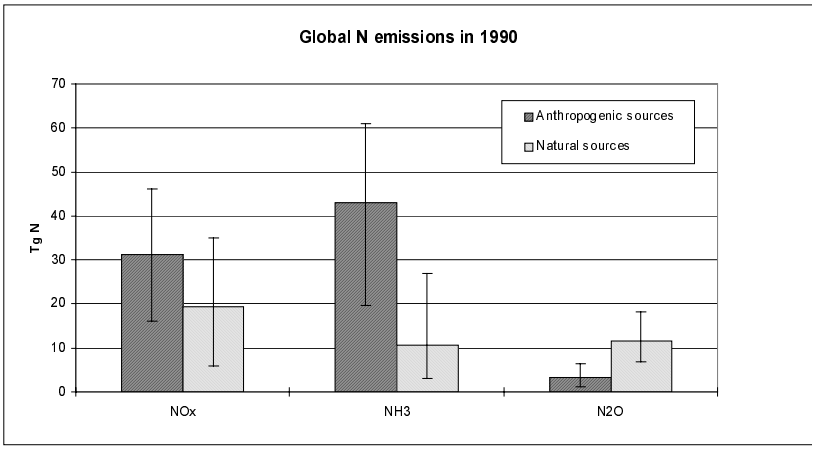


Fig. 4. Global anthropogenic and natural emissions of NO_x, NH_3 and N_2O and their absolute uncertainty.

Uncertainties

The uncertainty in the annual emissions can be assessed in space (for global, regional or country totals or at the grid-cell level) and by source (for all, major or detailed sources). The cause of the uncertainties as encountered in constructing the database, including key activity levels, emission factors, and the geographic distribution, will be briefly discussed.

For the economic activities such as fossil fuel use and industrial and agricultural production often reasonably accurate international statistics are available, and regional or global estimates are fairly precise. However, it is known that international statistics, on which EDGAR heavily relies, in some cases show substantial differences with national statistics of certain countries (Schipper et al., 1992). Activities such as biofuel use, waste burning and landfilling, are less well-documented than fossil fuel use.

Emission factors show a substantial variation according to the type of process. Exceptions are those factors that are strongly related to the physical or chemical characteristics of the process, such as fuel composition (CO_2, SO_2). Where possible, the average regional emission factors were estimated for aggregate source types in EDGAR.

The uncertainties in the geographic distribution of emissions are related to the maps used to distribute emissions or activities. For estimating uncertainty of emissions by grid cell, three aspects of the allocation maps used to distribute country emissions for certain activities on a grid within countries are important: (i) the accuracy of the relative intensities or densities (per country, if used to allocate national emissions). The accuracy of a map can be assessed by comparing different versions of the map — i.e. with different reference years and origin of data — such as in the case of the population density map for which GEIA inventories currently use two maps (Logan/Harvard and NASA-Goddard Institute of Space Studies), which were constructed for different years, with different resolutions of basic data and with a somewhat different methodology to fill in missing sections (rural population);(ii) the choice of the theme of the map. This needs to be evaluated, since other themes may result in quite different spatial distributions; (iii) the way in which border cells are treated in country-to-grid conversions.

In general it is much more difficult to quantify the uncertainty in the spatial distribution than that in the national activity levels or emission factors. Therefore, only the overall uncertainty in total emissions is given

Table 5

Indication of uncertainty in activity levels, emission factors and global and regional emission estimates; and type of spatial allocation for the major anthropogenic sources and subcategories of sources for NO_x, NH_3 and N_2O.

Main source	Subcategory	Activity data[a]	Emission factors[a]			Global total and regional emissions[a]			Type of spatial allocation[b]
			NO_x	NH_3	N_2O	NO_x	NH_3	N_2O	
Fossil fuel use	Fossil fuel combustion	S	M	L	M	M	M	M	p,s
	Fossil fuel production	S	-	L	-	-	M	-	p
Biofuel	Biofuel combustion	L	M	L	L	L	L	L	s
Industry/solvent use	Iron and steel production	S	M	-	-	M	-	-	s
	Non-ferro production	S	M	-	L	M	-	-	p
	Chemicals production	S	M	L	L	M	L	M	p,s
	Cement production	S	-	-	-	M	-	-	s
	Solvent use	M	-	-	-	-	-	-	s
	Miscellaneous	V	-	-	-	-	-	-	s
Landuse/waste treatment	Agriculture	S	-	M	L	-	M	L	d
	Animals (excreta)	S	-	M	L	-	M	L	d
	Biomass burning	L	L	M	L	L	L	L	d
	Agricultural waste burning	L	L	M	L	L	L	L	d
	Uncontrolled waste burning	L	-	-	-	-	-	-	s
Natural sources	Natural soils	M	L	V	L	L	V	L	d
	Grasslands	M	-	-	L	-	-	L	d
	Natural vegetation	M	-	-	-	-	-	-	d
	Oceans/wetlands	M	-	L	L	-	L	L	d
	Lightning	S	L	-	-	L	-	-	d
All sources		-	-	-	-	M	M	L	p,s,d

- indicates that no data are available for this source, or not applicable (source not identified).

[a] S = small (10%); M = medium (50%); L = large (100%); V = very large (>100%); - = not applicable.

[b] p = point sources known; s = surrogate distribution function used (e.g. population distribution); d = diffuse source (allocation e.g. from land cover databases).

Table 6

Calculated aggregated emission factors for NO_x (g NO_2 GJ^{-1}) from fossil fuel combustion in EDGAR V2.0, used to develop default emission factors for the Revised IPCC Guidelines for greenhouse gas emission inventories (IPCC, 1997)

Fuel type	Main sector[a]	Global average	OECD					Economies in transition		Other non-OECD regions					
			USA	Can.	W. Eur.	Japan	Ocean.	f.S.U.	E. Eur.	Lat. Am.	Africa	M. East	India reg.	China reg.	East Asia
Solid	Industry	270	560	190	300	180	250	270	310	180	240	180	250	240	200
Solid	Power generation	310	350	310	200	390	340	330	140	370	390	300	380	390	360
Solid	Total other sector	80	80	80	80	90	80	80	60	80	80	70	80	80	80
Solid	Non-road surface transport	270	–	–	190	–	270	270	180	270	270	180	270	270	–
Liquid	Industry	60	60	60	70	40	70	60	100	60	70	50	60	50	60
Liquid	Power generation	200	170	240	230	120	100	260	190	230	180	150	200	220	220
Liquid	Total other sector	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Gasoline	Road transport	600	700	700	700	200	700	500	500	500	700	500	300	500	400
Diesel	Road transport	800	700	700	700	800	700	900	1000	900	1000	900	900	900	900
LPG	Road transport	900	900	900	900	900	900	–	–	900	–	–	–	–	900
Liquid	Non-road surface transport	700	600	600	700	700	600	600	1000	900	900	900	900	700	800
Gas	Industry	160	270	110	150	110	110	110	130	110	110	110	110	110	110
Gas	Power generation	160	200	150	150	150	150	150	190	150	150	150	150	150	150
Gas	Total other sector	60	50	50	80	50	50	50	60	50	50	50	50	50	50
Gas	Surface transport	–	–	–	–	–	–	–	–	–	–	–	–	–	–

– indicates no data available.

[a] Industry excludes the energy sector; power generation includes industrial electricity production and cogeneration; total other sector includes: residential, commercial, other/non-specified; non-road surface transport rail, inland water, other/non-specified.

(Table 1), and the order of magnitude of the uncertainty in estimates at the regional level stemming from uncertainty in emission factors and activity levels for the three N gases and for the major sources (Table 5). The results show that the uncertainty estimates for emissions differ substantially according to the cross-section made in space, by source and by compound. Sources with a diffuse nature (generally associated with land use and agriculture) show highest uncertainties in regional estimates. Commonly the activities for these sources are based on reliable and consistent statistics, e.g. for animal population, land use and fertiliser consumption. However, data on agricultural management needed to derive emission factors are often lacking or incomplete (see e.g. Bouwman et al., 1997).

Emissions for specific, well known, local (point) sources or sources associated with human population concentrations (such as industrial sources, power plants and other sources related to fossil fuel combustion, based on reliable statistics) have lowest uncertainties in regional and global estimates.

Use of the emission inventories

Data from EDGAR were already used for a number of policy-oriented and scientific applications. Policy-oriented applications include: (i) EDGAR data were used for developing Dutch policy on air traffic; (ii) aggregated emission factors for major anthropogenic sources of NO_x were calculated with EDGAR for developing revised 'IPCC Guidelines for National Greenhouse Gas Inventories' of the Intergovernmental Panel on Climate Change (IPCC, 1997) as presented in Table 6; (iii) data were provided to the UN secretariat of the Framework Convention on Climate Change (UNFCCC); and (iv) EDGAR was used for assisting in evaluations of completeness and consistency of inventories submitted to the UNFCCC (Van Amstel et al., 1997).

Regarding scientific applications, Bouwman and Taylor (1996) have used an atmospheric tracer transport model to test the GEIA/EDGAR inventory of N_2O on 1°×1°. For this purpose additional assumptions were made on the seasonal variation of the different source categories. Because the model correctly reproduces the latitudinal gradient and seasonality of CFC-11 and other tracers, it was assumed that the inconsistency with atmospheric observation of N_2O concentrations is not caused by biases in the model. Therefore, discrepancies in the results indicate that misrepresentations in the emission inventories may cause exaggeration of the seasonality. It was concluded that a lack of monitoring stations in continental interiors makes it difficult to test hypotheses on sources and sinks of atmospheric N_2O with the available observational data.

EDGAR data and scenarios on grid of NO_x emissions have been used in atmospheric models to assess its effects as a precursor of tropospheric ozone. Furthermore, studies have been conducted into the consequences of its contribution to atmospheric deposition of N (Galloway et al., 1994) and the contribution of emissions from aircraft and surface sources to ozone in the upper troposphere (Schumann, 1995), for which a comprehensive assessment was made by Lee et al. (1997) of completeness and accuracy of existing inventories.

The recently published NH_3 inventory is now being used by several research groups worldwide. However, so far no results have been published. Developers and users are in contact in order to communicate disagreements between results of atmospheric models and emission inventories.

Policy options

The sectoral and regional dimension of the inventories is useful in assessing the global and regional reduction potential of control options available for reducing emissions. For NO_x fairly effective options for emission reduction are available. Emission of NO_x from road transport, particularly important in industrialised countries, can be drastically reduced by equipping automobiles with a three-way exhaust catalyst. For both electricity generation and industrial combustion, several options are available, such as the installation of low NO_x units by application of, for example, Selective Catalytic Reduction (SCR) technology. Besides these technological measures, energy savings programmes for industrialised countries are desirable with respect to the reduction of NO_x emissions. Uncontrolled burning of agricultural residues could be reduced by applying strict regulations combined with different agricultural practices.

Optimising animal feeding, a change in waste management and optimising the use of N fertilisers are key to achieving reductions of global and regional NH_3 emissions. Limiting biomass burning (savanna burning, deforestation, agricultural-waste burning in the field) would also reduce NH_3 emissions, especially in Africa, Latin America and south-east Asia. However, this option is much more difficult to institute than the above technical options.

Although there is a substantial uncertainty in the strength of some sources of N_2O, it is clear that the largest potential for emission reduction can be achieved in food production systems. More efficient use of nitrogen in agricultural practices could result in large emission reductions on the global scale without significant yield reductions. In addition, since a limited number of industrial-processes also contribute substantially, fast reductions could be achieved in these sectors when emission control technology would be applied.

When implementing emission reduction options for one compound, these may simultaneously affect the emission of other compounds favourably or adversely. Many examples can be given of such interrelations, such as catalysts in passenger cars to reduce NO_x emissions, which cause higher N_2O emissions than traditional exhaust systems; incorporation of manure in the soil to reduce NH_3 emissions, but simultaneously increasing N_2O emissions; lowering ground water levels may reduce CH_4 emissions but simultaneously lead to an increase in N_2O; temporary drainage of paddy rice fields leads to lower CH_4 but higher N_2O emissions.

Recommendations

We have discussed the global inventories for annual anthropogenic emissions to the atmosphere of NO_x, NH_3 and N_2O, both on a $1°\times1°$ grid as well as on a regional and per country basis. We have also made an assessment of the uncertainties in the annual emissions for the different sources of the three N gas species, and we discussed the use of the inventories. We have illustrated that EDGAR can be used to generate various cross-sections of GEIA inventories at the global, regional and national scale in various formats. Turning to the improvement of the emission inventories, a number of important tasks can be identified. Many detailed suggestions for improvements have been given by Olivier et al. (1996) and Bouwman et al. (1995, 1997). Here we will focus on four major improvements, related to the data used, temporal distribution of emissions, geographic distributions and approaches to validation.

Data

Tables 1 and 5 clearly show that, from the perspective of total N emissions, reducing uncertainties in total emissions can best be achieved by improving data for: (i) emission factors of NH_3 from animal excreta, in particular for cattle. This requires better data on manure management practices, in particular for cattle; (ii) emission factors of NO_x from fossil fuel combustion, in particular from road transport and power plants; (iii) both activity data and emission factors of biomass burning: savanna burning, biofuel use, agricultural waste burning and deforestation. Figure 3, in conjunction with Tables 2 to 4, shows for which regions improvement of current source-specific data will have the highest effect on reducing overall uncertainties. Natural nitrogen sources with the largest uncertainty ranges are soil emissions of NO_x and NH_3, lightning emissions of NO_x and oceanic emissions of NH_3 and N_2O.

Temporal resolution

The spatial resolution of the inventories matches that of the current CTMs, which generally use $5°\times5°$ fields at

the Earth's surface. However, comparison of state-of-the-art atmospheric chemistry transport models (CTM) and emission inventories indicates that there is a wide gap regarding the temporal resolution. Current CTMs describe processes with a time step of 1 to 6 hours. Except for the N_2O inventory, which has a monthly temporal scale, and the oceanic NH_3 concentrations and fluxes, all emissions presented in this paper are annual estimates. In particular for gas species with a short atmospheric lifetime (less than 1 day) this discrepancy between CTMs and emission inventories is important. A major improvement would be to develop future emission inventories on a monthly, decadal or daily scale. Separate routines could be developed to calculate the distribution of emissions on smaller time scales. However, on the basis of the available data it is very difficult to produce temporal distributions of emissions, in particular for the diffuse biogenic and natural sources such as soils and water bodies. Diffuse sources generally have temporal flux patterns of trace gases which vary in space, and spatial aggregation or generalisation — which is unavoidable when data are sparse such as in global inventories for these environments —causes considerable loss of information on temporal patterns of fluxes.

Sophisticated and carefully chosen schemes to stratify ecosystems or landscapes may help reducing the loss of information on temporal variability caused by aggregation or generalisation. Combined with stratification schemes, the firmest basis for scaling involves the development of an understanding of the mechanisms that regulate spatial and temporal patterns of processes, and describing these mechanisms in models. Flux models have three major advantages: (i) models are descriptions of current process knowledge, which is to be preferred above simple rules such as those applied in CTMs to produce temporal distributions; (ii) models can be used to calculate grid-based emissions on the basis of the above stratification schemes. This enhances the spatial resolution compared to the traditional emission-factor based inventories for diffuse natural and biogenic sources, such as Yienger and Levy (1995) for NO_x and Bouwman et al. (1997) for NH_3. The "true" spatial resolution in these emission factor approaches is not the grid, but biomes or ecosystems for which the emission factors are developed; (iii) the internal consistency of CTMs is improved by incorporating flux models.

For the emissions from industrial sources and those from fossil fuel combustion it is less difficult to produce temporal distributions of emissions, based on activity data, season or temperature, day and night cycles of production and use, etc.

Spatial distribution

Many anthropogenic emissions are distributed according to some surrogate distribution, often human population densities (Table 5). This may be quite realistic in the case of some sources, such as fuel combustion in households and road transport. However, for some other sources, such as industrial processes and agricultural residue burning, the use of population densities may introduce important, but unknown errors in the spatial distribution. It can not be expected that major improvements will be achieved in the development of spatial distributions for all individual sources within the coming 10–20 years.

Validation

Major improvements in the spatial and temporal distributions of emission estimates may be achieved by validation. For global inventories the most common approaches to validation are forward modelling with CTMs, or by inverse modelling. In forward modelling approaches, emission inventories are used to drive atmospheric models to calculate trends, patterns and distributions of atmospheric concentrations (for N_2O in particular) and dry and wet deposition (for NH_3 and NO_x). Validation can be done by comparing atmospheric observations with model results. The disadvantage of this method is that it is difficult to separate the errors stemming from the emissions or those from the CTM itself. In the inverse modelling approach sources are calculated from the atmospheric concentrations. Particularly the latter method seems very promising, although it is a difficult task to develop inverse models for highly reactive species, due to the complexity of the inverse problem.

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4. Global Inventories with Historical Emission Trends: EDGAR 3.2

4.1 Introduction

The compilation of emission inventories for a series of years provides other, additional aspects to be considered than in the case of inventory construction for a single year. In general consistency over time is an important quality aspect to evaluate the significance and consequences of emission trends. For the direct estimation approach three specific questions need to be addressed:

- Are the statistics used as activity data for each source consistent over time or can trend breaches be observed due to methodological changes that significantly influence the activity levels and that have not been implemented in the whole time series?
- Can emission factors assumed to be constant within the time period considered or are the changes significant, i.e. of the order of the changes in the activity data?
  In case of major technological changes the impact on emission factors will in most cases be easily recognised. However, gradual changes over the time period considered may not be marked easily. When compiling trend inventories for several decades, this possibility should be carefully checked for large sources.
- Can the spatial distribution of sources assumed to be relatively constant within the time period considered or need migration in specific sources to be explicitly considered?
  Examples are start-up or closure of industrial facilities (so-called point sources), or the shift of rural population to urban areas.

In this chapter we present the analysis made for the compilation of a new global inventory of anthropogenic sources of methane for the last 25-year period, which is part of the EDGAR 3.2 inventories. For estimating emissions from landfills and wastewater disposal and their trends, which were estimated rather simple or not at all in EDGAR V2.0, we developed sector models similar as the IPCC recommends in her inventory guidelines. The results are discussed at various spatial levels, including the estimated uncertainty of the resulting inventory in both annual estimates as well as the uncertainty in the trend. According to our analysis in this period anthropogenic emissions have increased by 22% (± 18%) about 50 Tg/yr from 250 Tg/yr to 300 Tg/yr (annual uncertainty ±23%), whereas the increasing trend is levelling off since the late 1980s (95% confidence interval). In addition we propose a new estimate of the source strengths of natural sources of 230 Tg/yr, which fits well into a global budget with a total global source strength of approximately 530 Tg/yr emissions in the 1990s.

Apart from the question of the accuracy of the emission estimate for a particular year, here the question arises how robust are the calculated emission trends? In answering this question possible correlations between years need to be taken into account, certainly when the assumption was made that emission factors have remained constant over time. The uncertainty in the *trend* of anthropogenic methane emissions was estimated by applying the IPCC trend uncertainty estimation method, originally developed for individual countries, to our global inventory. We analysed two cases: for the world as a whole and for three regions OECD'90, EIT and LDC. In the latter case we simulated correlations of emission factors within each region as well as region-specific uncertainties in the underlying data. From these calculations we conclude that in this case refining by using a more homogeneous three-region uncertainty assessment does not substantially change the calculated annual and trend uncertainties.

4.2 A global emission inventory of methane sources with trend data for the period 1970-1995

An edited version of this paper will be submitted to the *Journal of Geophysical Research:*
Olivier, J.G.J., A.J.H. Visschedijk, J.A.H.W. Peters, J. Bakker, J.J.M. Berdowski, J.P.J. Bloos (2002) *A global emission inventory of methane sources with trend data for the period 1970-1995 and outlook to 2020.*

Abstract. A global inventory of annual methane emissions was developed for the 1970-1995 period with a focus on the historical methane emission trend of anthropogenic sources on a per country basis and on a 1x1 degree grid, supplemented with estimates for natural sources modelled by others. The global reference dataset for 1970-1995 was compiled using a transparent methodology and, whenever possible, well-established and well-documented emission factors - refined where necessary to take into account structural changes over time. This work was part of the construction of the EDGAR 3.2 dataset. Special attention was paid to incorporating structural changes in coal mining, rice production and composition of landfilled waste that affect the emission factors over time and to methane recovery from coal mines, landfills and wastewater treatment plants. Moreover, to estimate the emissions from landfills and wastewater disposal, we used sector-specific models. Other sources included are fossil fuel use, biofuel use, animals, agricultural waste burning, large-scale biomass burning in tropical and temperate regions, landfills and wastewater handling. According to our analysis in this period anthropogenic emissions increased by 22% (±18%) or about 50 Tg/yr from 250 Tg/yr to 300 Tg/y (annual uncertainty 23%), whereas the increasing trend is levelling off since the late 1980s (95% confidence interval). Combined with an estimate of natural sources of about 230 Tg/yr we estimate global total source strength at 530 Tg annual emissions in the 1990s.

1. Introduction

Several global methane emission inventories have been compiled, e.g. Matthews and Fung (1987), Lerner *et al.* (1988), Fung *et al.* (1991), Olivier *et al.* (1996; 1999) and Denier van der Gon (1999; 2000). A few inventories have been compiled that span a historical period, e.g. Stern and Kaufmann (1996) and Van Aardenne *et al.* (2001). These inventories, however, only focussed on one particular year or source category or were mainly focusing at long term trends at the total global level using simplified methodologies for that purpose. This study attempts to establish a global reference dataset for 1970-1995 using a transparent methodology and, whenever possible, well established and documented emission factors – factors describing the emission rate per year per unit of activity of a specific source – refined where necessary to take into account structural changes over time. The dataset may serve both scientific and policy applications. We describe the methodology, document data sources of activity data and emission factors, and discuss the results at various spatial levels, including the estimated uncertainty of the resulting anthropogenic inventory in both annual estimates of the global total as well as the uncertainty in the trend. Also a comparison is made with the other published inventories and uncertainty estimates.

This work was part of the construction of the EDGAR 3.2 dataset. EDGAR 2.0 provided global annual emissions of greenhouse gases in 1990, both per region and on a 1°x1° grid (Olivier *et al.*, 1996; 1999). The EDGAR (*Emission Database for Global Atmospheric Research*) project has been carried out jointly by the Netherlands' *National Institute for Public Health* (RIVM) and the *Netherlands Organisation for Applied Scientific Research* (TNO) (Olivier *et al.*, 1996, 1999). The overall aim for EDGAR 3 was to update the inventories from 1990 to 1995, and for direct greenhouse gases also to 1970, and to include the 'new' groups of fluorinated greenhouse gases HFCs, PFCs and SF_6. The work is linked into and part of the *Global Emissions Inventory Activity* of IGBP/IGAC (Graedel *et al.*, 1993). For a concise description of the overall methodology and data used to compile Version 3 we refer to IEA (2001), Olivier and Berdowski (2001) and Olivier *et al.* (2001).

The new inventory can be used to compare with atmospheric observations of methane concentrations (annual or trends), with official national inventories and other methane inventories and can be used in atmospheric chemistry and transport models. To a large extent we used default emission factors recommended by the *Revised 1996 IPCC Guidelines* (IPCC, 1997) for the 1990 inventory, which also enables comparison of these factors with those used in other scientific inventories and in official emission inventories. The 25-year period was chosen because of the common availability of international statistical data for the main anthropogenic sources of methane. These include fossil fuel production, animal husbandry, rice cultivation, and waste (human population and gross domestic product) and other sources of greenhouse gases such as fossil fuel combustion and the manufacture of specific industrial products.

The uncertainty in *annual* emissions and in the *trend* of anthropogenic methane emissions was estimated by applying the IPCC trend uncertainty estimation method, originally developed for individual countries, to our global inventory. We analysed two cases: for the world as a whole and for three world regions. Our estimate of the uncertainty in emissions at global level is compared to other studies. We also discuss the uncertainties at country level including a

reference to 'default' estimates provided by IPCC expert groups (IPCC, 2000). Finally, we discuss the largest uncertainties in the gridded emission inventories.

Finally, we do not discuss the trends in gridded emissions here. Also the temporal variation of the sources such as seasonality is not discussed. This will be subject of discussion in another paper. Also the trends in gridded emissions are not discussed here.

2. Approach and research priorities

Our objective was to compile a global inventory of methane emission sources for the period 1970-1995, providing realistic trend estimates at global, country, and 1x1 degree grid level. Our focus was to compile a historical methane emission trend of annual emissions for anthropogenic sources on a per country basis and on a grid basis, supplemented with consistent estimates for natural sources based on a review of the literature.

Globally the largest anthropogenic sources are enteric fermentation by animals, rice cultivation, coal production, landfills, and gas transmission. Together they account for almost 80% of the global anthropogenic total according to the EDGAR 2 dataset for 1990. Smaller sources that account for another 15% are production of natural gas, biofuel combustion and large-scale biomass burning (agricultural waste, deforestation, savannahs) (Olivier *et al.*, 1999). Based on our previous experiences in compiling a dataset for 1990 we concluded that for the following sources basic national statistics exist, but emission factors depend on more detailed structure of the emission source:

- *animals*: by animal type, with cattle split into dairy cattle and non-dairy (meat) cattle, and by other subtypes in terms of food composition or weight;
- *rice cultivation*: different type of ecologies, notably irrigated, rainfed, deepwater and upland;
- *coal production*: for hard coal production a distinction should be made between surface mining (open pit) and underground mining, in addition to distinguishing the two main coal types hard coal and brown coal;
- *landfills*: this is a difficult source type, for which actual annual emissions depend of various parameters such as the fraction of waste dumped in landfills, not only in the year of emissions but also in preceding years, and the fractions of (a) degradable organic carbon (DOC) in the waste, (b) DOC ultimately dissipating as landfill gas; (c) methane in landfill gas;
- *gas transmission*: emissions depend on maintenance and operation practices as well as materials used for gas pipelines, notably the leaky grey cast iron distribution pipelines.

Another source of methane emissions that has recently been identified as a probable large source is wastewater treatment and disposal, in particular latrines and open sewers in developing countries (Doorn *et al.*, 1999). In addition, for a few sources methane recovery may substantially affect net emissions of specific countries: landfills, coal mining, and wastewater treatment plants (Bibler, 1998; National Communications to the UN Climate Change Secretariat).

Activity data for which national statistics are not readily (openly) available at the required level are: (a) subcategories of animal types, except for a split into dairy and non-dairy cattle; (b) rice production by ecosystem type; (c) separate figures for underground and surface mining of hard coal; (d) amounts of waste deposited into landfills and its composition; (e) the length of national gas transmission and distribution networks – let alone details on pipeline types such as cast iron, steel, PVC or polyethene; (f) amounts of biofuel and (g) large-scale biomass combustion and (h) amounts of agricultural waste combusted on-site. However, in order to make a fair estimate of how annual emissions have changed over the last decades, structural changes over time need to be taken into account, where relevant. Information from source experts showed the following changes might be relevant:

- increasing fraction of surface mining of coal, as a result of increasing technically and economically ability to remove the overburden of shallow coal seams;
- productivity increases of livestock, such as milk yield per cow and (carcass) weight per animal, due to changes in animal breeds and optimising their feed intake;
- increasingly rice cultivation areas are being irrigated, but more importantly changes in rice types, e.g. through introduction of hybrid types, and amounts of organic amendment, have effectively reduced the methane emission factor per unit of harvested area (Denier van der Gon, 1999, 2000);
- in a number of countries (USA, Western Europe, India) the fraction of waste deposited into landfills has decreased significantly in the 1970-1995 period, while in other countries (Eastern Europe, former SU, Latin America) the so-called *Methane Correction Factor* has increased due to changes in landfill types/compacting practices.
- for gas transmission two aspects could substantially influence the overall emission factors: gradual phasing out of old grey cast iron distribution pipelines with their leaky lead-oakum socket joints and changing practices within the gas industry in the former Soviet Union in the early 1990s.

Information about the typology of national gas distribution networks is scarce and very hard if not impos-

sible to obtain. With respect to emissions from the Russian gas and oil industry, different reports are not conclusive as to that the effect has been on fugitive emissions of gas from the various pipeline systems. Furthermore, data reported by national governments to the secretariat of the *UN Framework on Climate Change* (UNFCCC) suggest that in general changes in animal subtypes or in the food composition are not significant, at least not in the OECD countries in the 1990s. An exception could be made for dairy cattle of which the emission factors in five OECD countries as reported in the 1990s increased by about 0.6 (± 0.2) % per year. Dairy cattle, however, only contribute about 15% to global total emissions from animals. Therefore, we decided not to investigate structural or temporal changes over time for these gas transmission systems and livestock.

The information above provided the rationale for our approach. Firstly, compiling statistics for basic activity data per country for the period 1970-1995 for all anthropogenic sources. Secondly, compiling a comprehensive and consistent set of emission factors, where necessary at country level, for all identified anthropogenic sources, based on well established and well documented emission factors. Thirdly, including a plausible description of landfills and wastewater handling. Fourthly, providing a sound basis for trend estimates of methane emissions in the 1970-1995 period by taking into account changes in emission factors over this time period for the sources where this could be expected. Thus, we focussed our study on the inclusion of structural changes within the last 25 years in coal mining and rice production and on the compilation of a dataset for landfills and wastewater handling based on national characteristics, whenever possible.

3. Methodology and basic data sources

As general approach we start estimating emissions at country level with activity data and emission factors at national level, which can subsequently be aggregated to regional subtotals and further disaggregated to a 1x1 degree grid level. For allocating national emissions to the grid, we use source-specific grid maps to distribute per source total emissions per country to corresponding grid cells within the country: the relative intensity of the levels in the grid cells within the country borders acts as allocation function. The same grid maps were used for all years; no attempt was made to correct for changes in the spatial distribution of activities within the countries. Although this is an approximation, the selected maps themselves are already a proxy for the actual source distribution and for most sources it can be expected that the distribution has changed only to a limited extent within the last decades. For the selection of input data for the 25-year dataset we used the same approach as taken for the 1990 data in EDGAR 2 as described in Olivier *et al.* (1999). Basic activity data were mostly taken from international statistical data sources (e.g. IEA, UN, FAO) for reasons of efficiency, quality control performed by the international agency and comparability across countries. However, for the 25-year period we needed to add the following elements to the primary activity data. For many countries interpolations and extrapolations were necessary to arrive at complete time series per country for 1970-1995, in particular for industrial production statistics. In addition, for statistics of the new countries of the former Soviet Union and former Yugoslavia we had to construct a modified dataset to achieve a complete time series for the new countries for 1970-1995 of which the sum converges to the older dataset for the total former SU and total former Yugoslavia, respectively. Emission factors were selected mostly from 'international' publications to ensure a consistent approach across countries. For the EDGAR 3 dataset of global CH_4 emissions we generally use methods and emission factors recommended by the *Revised 1996 IPCC Guidelines* (IPCC, 1997), which are generally well established and well documented. This also enables comparison of these factors with those used in other inventories. Cases where we depart from the IPCC approaches and IPCC emission factors are clearly specified.

3.1. Fuel use

3.1.1. Fossil fuel use

Data for fossil fuel production and use for 112 countries were taken from IEA energy statistics for OECD and non-OECD countries 1970-1995 (IEA, 1997). For the countries of the former Soviet Union we used a modified dataset to achieve a complete time series for the new countries for 1970-1995. Essentially, for the years prior to 1992 energy consumption per fuel type/sector for the total former USSR has been split according to the shares of the new countries in 1992, thereby overruling any figures in the datasets for the new countries for single years prior to 1991. Obviously, this is a simplification and introduces a discontinuity in the early 1990s since the old and new dataset often did not match well. Yet, in the absence of any or reliable data for the pre-1992 period we concluded that this was the best approach to get complete time series for these countries. For another 71 countries, the aggregated IEA data for the regions 'Other America', 'Other Africa' and 'Other Asia' have been split using the sectoral IEA data per region and total production and consumption figures per country of hard coal, brown coal, gas and oil from UN energy statistics (UN, 1998). Note that the EDGAR 3.2 data are based on IEA statistics published in 1997 and thus may differ somewhat from most recent IEA datasets; in particular for

the new countries of the former Soviet Union the IEA data may have been updated considerably. In addition, for estimating CH_4 emissions total hard coal and brown coal production data have been split into surface and underground mining based on various reports (general 1990 split: Mining Journal, 1994; former USSR: Flegan, 1994; China: Doyle, 1987; trends in the split: various national reports).

Emission factors from fossil fuel production and use are listed in Olivier *et al.* (1999). For coal mining the (gross) emission factors were based on Smith and Sloss (1992), since in the *Revised 1996 IPCC Guidelines* (IPCC, 1997) no default emission factors were given for generic underground and surface mining. The increasing trend of 10% in (gross) methane emissions from global coal production does not follow the increasing trend of total coal production of 60% in the 1970-1995 period (see Figure 1). This is, to a large extent, caused by the compensating trend of the shift from underground to surface mining. In particular in the USA the increase in (gross) emissions is 35% points less than the coal production, whereas in OECD Europe and in the former USSR the emission change in the last 25 years is about 15% points less. In calculating methane emissions from coal mining we included methane recovery amounts for ten countries, amounting to about 1 Tg in 1990, of which about half was allocated to the USA and Germany. Methane recovery in 1995 was estimated at 2 Tg (Thakur *et al.*, 1996; Bibler *et al.*, 1998; national reports to the *Climate Convention Secretariat*). This caused the 1970-1995 increase in global coal mine emissions to be 7% points lower, resulting in a net global increase in methane emissions from coal mines of 4%. The emission factors for gas transport plus distribution, related to total domestic supply of natural gas, are largely based on default IPCC factors prepared by Ebert *et al.* (1993). For gas and crude oil production methane emission factors have been calculated from estimates by Arthur D. Little (1989). Resulting methane emissions from fossil fuel production and transmission are presented in Figure 2.

A minor part of the total crude oil production emissions comprises emissions from oil loading into marine tankers, for which we used the exported crude oil as activity data. The magnitude of this part has been estimated with emission factors for oil loading from OLF (1993). The emission factors for petroleum refining and storage at the refinery were compiled by Veldt and Berdowski (Builtjes, 1992). These emission factors account for all combustion and fugitive emissions at the refinery site.

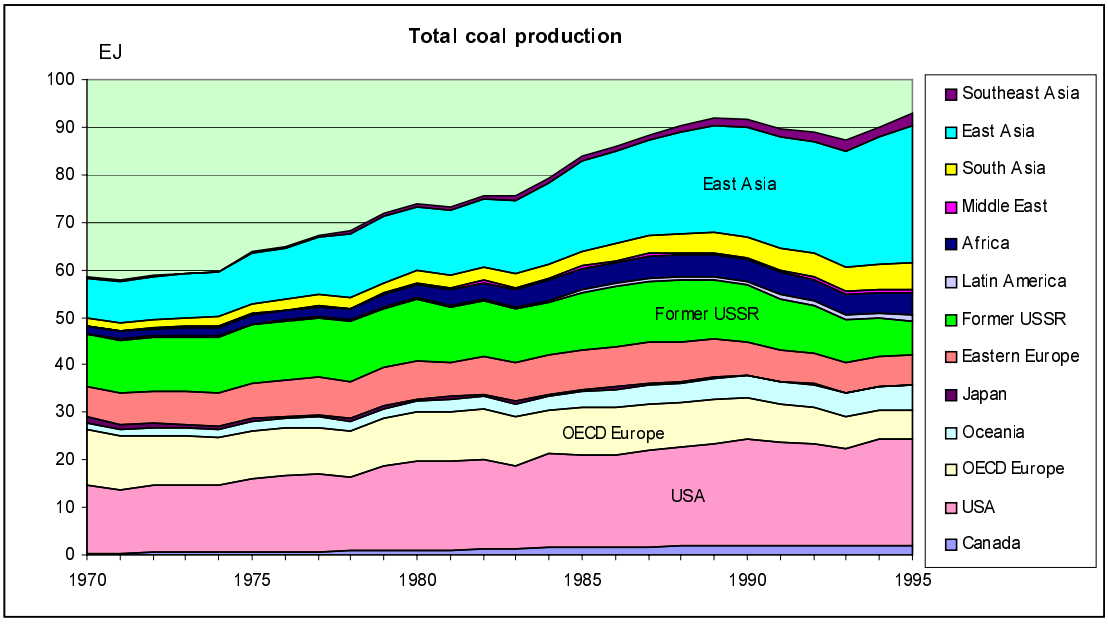

Figure 1. Total coal production 1970-1995 (unit: EJ).

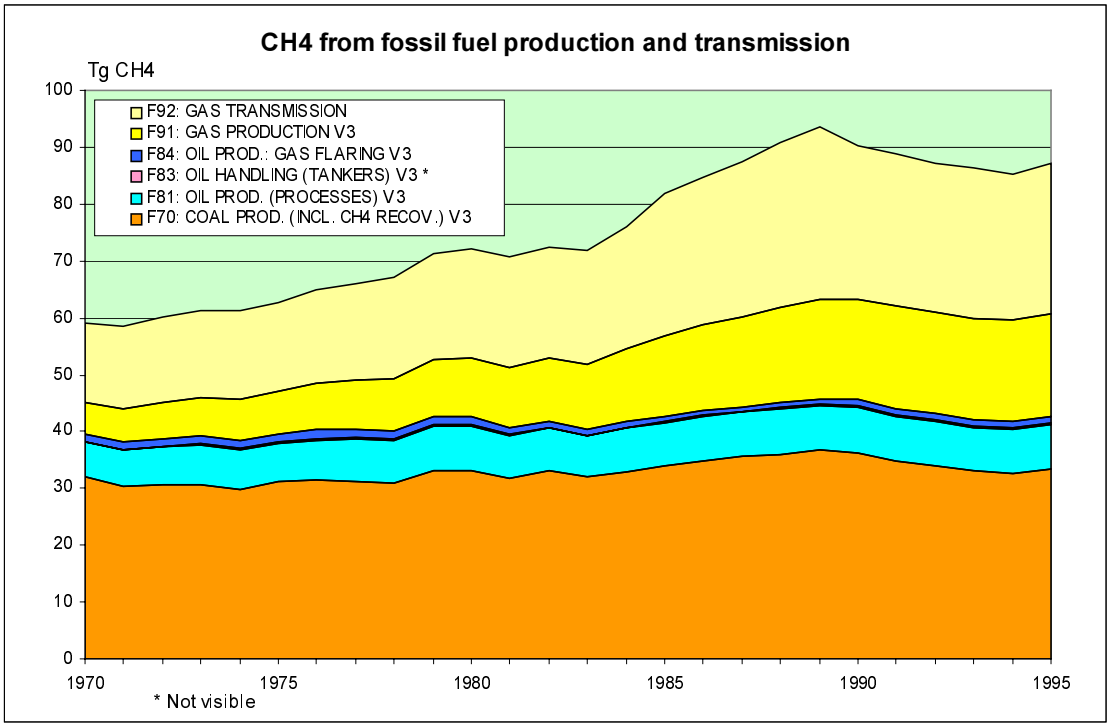

Figure 2. Trend of methane emissions of fossil fuel production and gas and oil transmission 1970-1995.

3.1.2. Biofuel use

For developing countries biofuel data in 1990 have been based on Hall *et al.* (1994) with splits of biofuel per type as in EDGAR 2.0 (Olivier *et al.*, 1996, 1999), including vegetal waste used as fuel. For developing countries the time series 1970-1995 was constructed by extrapolating the 1990 dataset towards 1970 and 1995, according to the trends in urban and rural population, using weight factors based on Hall *et al.* (1994) of 1/3 and 2/3, respectively. These factors should take into account that urban households tend to use either more efficient biofuels (charcoal) or more fossil fuels such as kerosene or LPG. A limitation of this approach is that changes in the *mix* of biofuels over time are not taken into account. An exception, however, was made for Latin American countries, where we used biofuel statistics by fuel type and sector from OLADE for the period 1970-1995 (OLADE, 1999, pers. comm).

To verify our approach for the other developing countries we compared the OLADE statistics with results of the procedure described above. For the 26 countries the extrapolation would result for fuelwood in an average decrease of 1% in the 1970-1990 period compared to a 3% decrease in total biofuel use according to OLADE statistics, thus rather similar to our proxy approach. For individual countries our extrapolated estimates ranged from 60%-points too low for Equador to 13%-points too high for Chili (excluding Brazil that has a special biofuel mix with charcoal use for iron production and ethanol use in road transport). For most of the larger countries, however, the differences are smaller, in the order of 5-20%. In OECD'90 and EIT countries (Economies-In-Transition, i.e. Eastern Europe and former Soviet Union countries) fuelwood and charcoal production and consumption data were based on FAO (1998), thereby replacing any IEA data for biofuel combustion in the 'Other sector' in these countries. For biofuel combustion in industry and power generation in OECD'90 countries, we still used the data as provided in the IEA dataset (IEA, 1997). We note that these data were often not provided for all years and all countries. The resulting dataset for biofuel consumption shows an increase in the total global amount of non-commercial biofuel use from 28 EJ/yr in 1970 to 33, 39 and 42 EJ/yr in 1980, 1990 and 1995, respectively. It is stressed, though, that these estimates are very uncertain.

Emission factors for biofuel combustion and charcoal production have been based on a review of available literature made for the *Revised 1996 IPCC Guidelines* (IPCC, 1997) (Table 1). Resulting methane emissions from residential biofuel combustion increase from 9 to 12 Tg/yr in the 1970-1995 period, whereas the small emissions from charcoal production increase to about 1 Tg in 1995.

Table 1. Emission factors in EDGAR 3.2 for biofuel combustion in the residential sector and for charcoal production (g/GJ)

Biofuel type	CH_4	N_2O	CO	NO_x	NMVOC	SO_2	NH_3	References
Fuelwood	300	4	5000	150	600	15	55	2,3,5,6,7,8,9,10,11,12
Charcoal	150	1	7000	100	100	20	55	2,3,6,8,9
Agricultural waste	300	3	5000	150	600	60	55	3,5,11
Dung	400	4	7000	250	800	400	55	2,3,5,11
Wood waste	400	4	4700	100	65	15	0	4
Charcoal production	1000	1	7000	10	1700	5	3	2,3,7,8,9,10

Sources: 2 (Berdowski *et al.*, 1993); 3 (Veldt and Berdowski, 1995); 4 (Olivier *et al.*, 1999); 5 (Smith and Ramakrishna, 1990); 6 (Smith *et al.*, 1993); 7 (Delmas, 1993); 8 (Delmas *et al.*, 1995); 9 (Brocard *et al.*, 1996); 10 (USEPA, 1985); 11 (Joshi *et al.*, 1989); 12 (Ellegard and Egneus, 1992).

3.2. Agriculture

3.2.1. Animals

Activity data for livestock numbers were taken from FAO (1997), which were combined with regional information on animal waste generated per head listed in IPCC (1997) to estimate the amount of animal waste. FAO animal numbers per country were used for the following categories: (a) enteric fermentation and waste by cattle (where a distinction was made into dairy and non-dairy cattle), sheep, goats, swine, buffaloes, camels, mules, asses and horses; (b) waste by other animals: poultry, ducks and turkey (FAO, 2000). In addition, we used caribou numbers from Lerner *et al.* (1988).

Other information on animal weight or food composition or their change over time on a country by country basis was unfortunately not available for this large source that accounts for about a quarter of global total anthropogenic methane emissions. Thus, we used the Tier 1 emission factors for CH_4 for enteric fermentation and for animal waste (confined and outside) from the *Revised 1996 IPCC Guidelines* (IPCC, 1997). To calculate the methane conversion factor per country we need the fractions of the countries in the three climate zones (cold, temperate, warm). These were calculated from the 1x1 degree grid map for non-dairy cattle from Lerner *et al.* (1988) and the annual average temperature per grid cell from New *et al.* (1999). Resulting emissions are presented in Figure 3, which clearly shows that enteric fermentation – notably by non-dairy cattle – is the dominant source of methane from animals contributing 50% to global total anthropogenic emissions; animal waste contributes only 10% to total animal emissions. Regions contributing most to animal emissions are Latin America and South Asia, with emissions rising in the 1970-1995 period by 50% and 30% from 12 to 18 Tg/yr and from 11 to 15 Tg/yr, respectively (Figure 4).

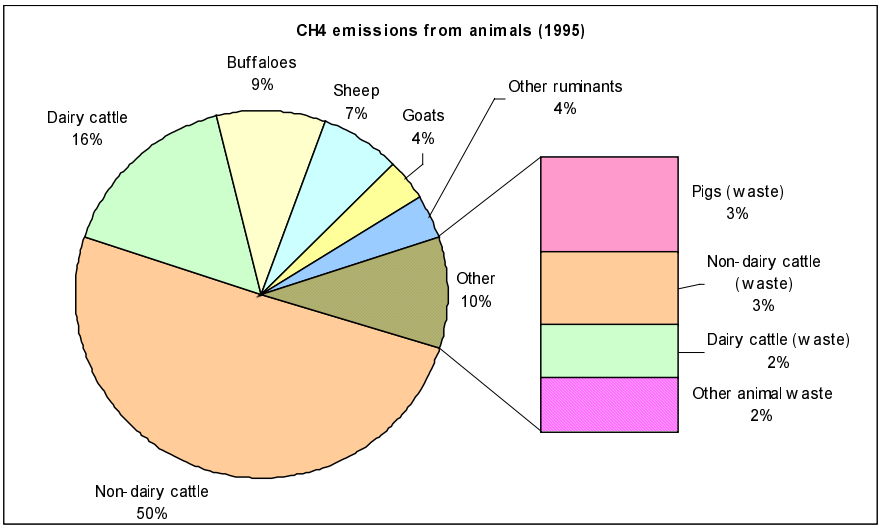

Figure 3. Methane emissions from animals in 1995 by ruminant species and animal waste category.

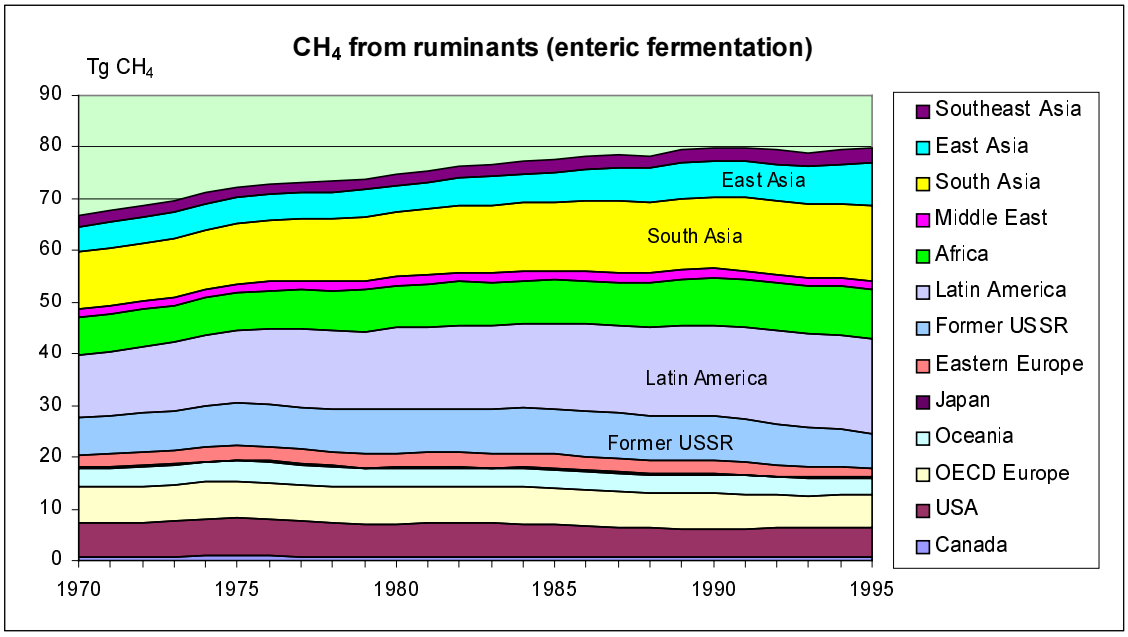

Figure 4. Trend in regional methane emissions from enteric fermentation.

3.2.2. Rice cultivation

Net crop production was taken from FAO (1997), with harvested areas of rice production split over different ecology types (rainfed, irrigated, deep water and upland) using the March 1997 version of the RICE-ECO database of FAO (Van Gnuu, 1997, pers. comm.). In addition, the total harvested area of rice production in China was increased by 40%, due to the official recognition that official harvested rice area statistics of China are largely underestimating the actual cultivated area (Denier van der Gon, 2000, pers. comm.).

We used country-specific emission factors for CH_4 for seven countries and global defaults for other countries for four ecosystem types of rice production: irrigated, rainfed, deepwater and upland rice, respectively. These were applied to country-specific rice production data for these types. The emission factors for CH_4 from rice production in 1990 were taken from a review by Neue (1997). For the period 1970-1990 we assumed an emission factor improvement (multiplication factor to get the emission factor for 1970) in the 1970-1990 period based on trend data for Indonesia, the Philippines, Thailand and for China in Denier van der Gon (1999, 2000):

- for irrigated rice in other South Asia, East Asia and Southeast Asia we used a multiplication factor of 1.81, which is the weighted average of data for Indonesia (1.83) and the Philippines (1.73); the same value was used for all OECD and EIT regions. For all other less developed regions we used the same multiplication factor of 1.81 as for China;
- for rainfed rice we used the figure of 1.17 for Southeast Asia, which is the weighted average of data for Thailand (1.09) and the Philippines (1.73); the same value was used for all other regions;
- for deep water rice we used the same factors as for irrigated rice.

The four mentioned countries cover 50% of global methane emissions from rice production. In this way we included in the methane emissions trend for 1970-1990 the influence of the changing mix of ecosystem types and of the rice varieties used and the declining amounts of organic inputs in rice cultivation. The resulting trends are presented in Figures 5 and 6. It shows that with our assumptions the emissions have decreased by 27% in the 1970-1995 period, while the harvest area has slightly increased by 10%, predominantly by increasing the irrigated area by almost 30%. More than 90% of 1995 rice emissions stem from South, East and Southeast Asia regions.

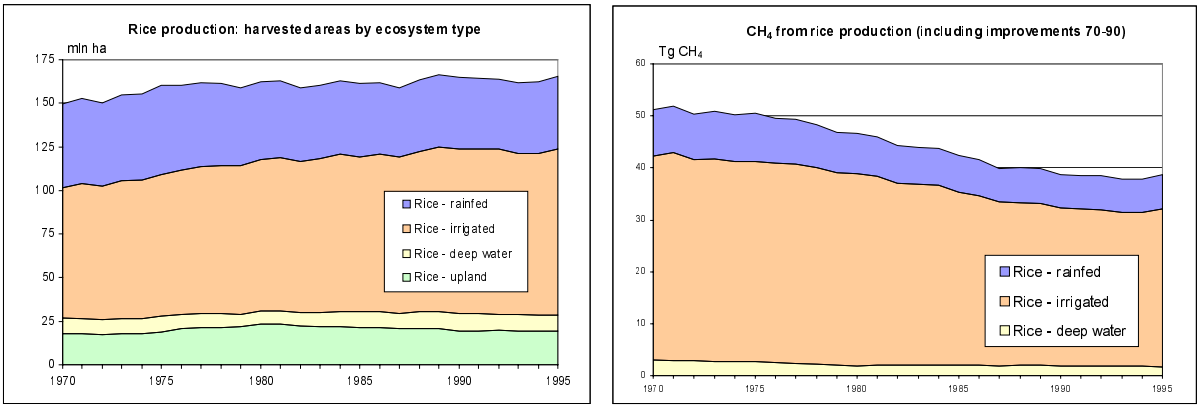

Figure 5. Trends 1970-1995 in rice cultivation by ecosystem: harvested area (left); methane emissions (right).

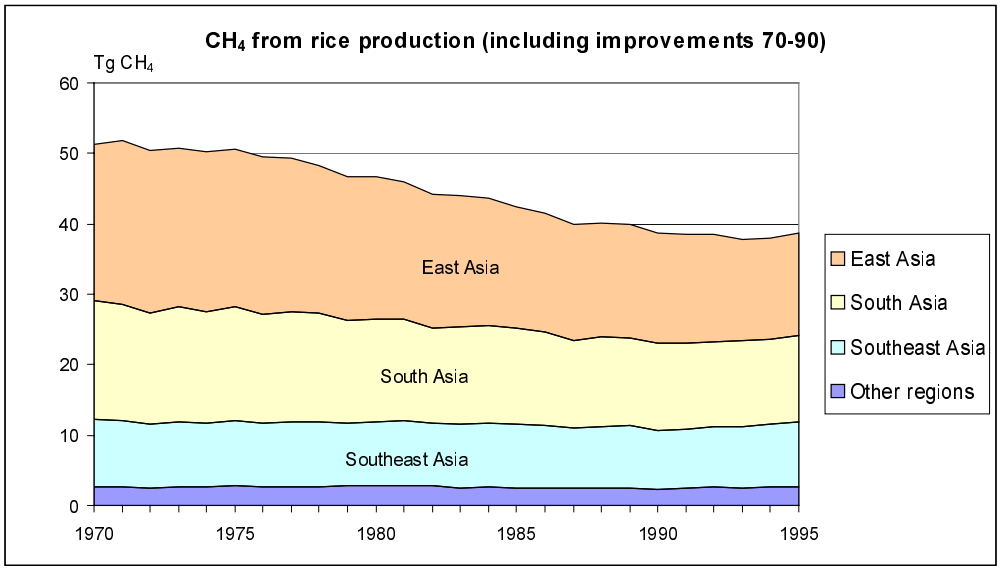

Figure 6. Trend 1970-1995 in regional methane emissions from rice cultivation.

3.2.3. Agricultural waste burning

The fraction of agricultural waste associated with net crop production was based on a recent study by Smill (1999). The fractions of agricultural residues burned on-site have been based on an analysis made by Bouwman (1997) and data reported in the Second National Communications to the Climate Secretariate of USA, Japan and Australia. We assume 5% burning in OECD regions, 20% in EIT and 40% in developing regions. Exceptions are Oceania where we used a percentage of 30% (Nat. Com. Australia) and OECD Europe where we assumed a decreasing trend from 40% in 1980 to 5% in 1995 based on data for the UK in Lee and Adkins (1994). The resulting trend in amounts burned on site is presented in Figure 7. The 40% for developing countries includes the amounts used as biofuel; for OECD and EIT the fractions are assumed to refer to field burning only. The resulting fractions of agricultural waste burned on the field is presented in Table 2, where these are presented per EDGAR3/IMAGE2 region for the period 1970-1995. Due to varying percentage of amounts used as biofuel in LDC regions, the effective fraction of field burning also varies in these regions. For OECD regions the fractions are assumed to refer to field burning only, and are assumed to remain constant, except for OECD Europe as discussed above. The present fractions burned in developed and developing countries are now considerably lower than in EDGAR 2.0. The emission factors (Table 5) were selected from a range of sources and are – within the uncertainties – in line with the recent compilation by Andreae and Merlet (2001). However, the emission factors of CH_4 and CO from deforestation and of NO_x from savannah burning differ from the IPCC defaults (Table 5).

Table 2. Regional fractions of agriculture waste burning on-site in EDGAR 3.2 (excluding per LDC country the amount used as biofuel) (unit: % field burning of total agricultural residues)

EDGAR 3 region	IM2	1970	1975	1980	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Canada	1	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
USA	2	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
OECD Europe	9	40%	40%	40%	30%	28%	26%	24%	22%	20%	15%	10%	8%	7%	5%
Japan	17	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Oceania	16	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%
Eastern Europe	10	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
Former USSR	11	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
Latin America	3	17%	17%	19%	21%	19%	20%	19%	19%	21%	21%	21%	20%	21%	21%
Latin America	4	22%	21%	18%	16%	16%	15%	16%	16%	15%	16%	16%	18%	17%	17%
Africa	5	25%	20%	22%	21%	23%	17%	24%	24%	19%	20%	14%	14%	22%	13%
Africa	6	23%	24%	24%	23%	22%	22%	22%	23%	22%	23%	23%	23%	23%	23%
Africa	7	24%	24%	20%	21%	20%	21%	20%	21%	22%	21%	20%	27%	26%	27%
Africa	8	21%	21%	24%	22%	22%	21%	22%	24%	22%	21%	23%	26%	24%	22%
Middle East	12	31%	31%	32%	31%	31%	31%	32%	31%	31%	31%	30%	30%	31%	31%
South Asia	13	0%	0%	2%	3%	3%	1%	3%	4%	3%	2%	3%	4%	5%	4%
East Asia	14	5%	7%	5%	3%	3%	2%	3%	3%	2%	2%	2%	2%	2%	2%
Southeast Asia	15	23%	22%	23%	22%	23%	23%	23%	22%	22%	21%	21%	20%	21%	21%

Note: IM 2 = IMAGE 2 region.

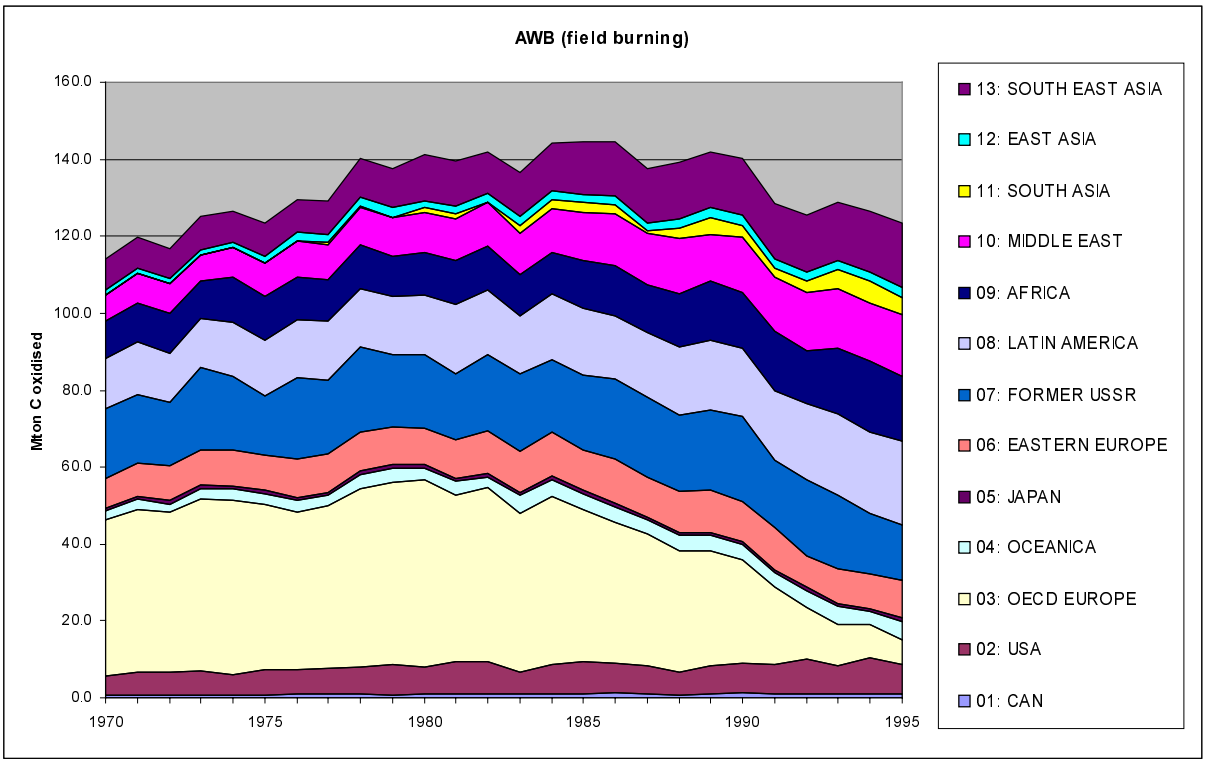

Figure 7. Trends 1970-1995 in agricultural waste burning (on site).

3.3. Waste handling

3.3.1. Landfills

Activity data with a global coverage for annual waste generation – so-called municipal solid waste (MSW) – or waste dumped in landfills are not regularly published on a per country basis, let alone on a comparable basis. Therefore, we had to construct a comprehensive dataset, covering both all countries and the 25 year period based on available partial datasets. However, we note that available national waste data may sometimes include other waste streams, such as industrial waste or demolition waste from buildings or roads, and that this is not always clearly expressed.

We used a correlation of waste generation per capita to per capita income per country to estimate total national waste generation of a country in a specific year for estimating global and per country landfill emissions in 1990 as well as the historical trends. Based on the notion that the amount of waste generation per capita increases with income but saturates at higher income levels, we fitted four available international datasets of waste generation in 1990 to an exponential curve: $Y = b*X^m$, where Y = waste/cap (kg/cap/yr), X = GDP/cap (US$/cap, constant prices), b = 15.5 and m = 0.32 (see Figure 8). These datasets are described in IPCC (1997), Adler (1994), CEC (1997) and Van Beek (1997). This fit was also used to estimate the activity data for 1990 for countries not mentioned in IPCC (1997) and Adler (1994). Country-specific fractions of total MSW generated that are disposed into landfills were based on IPCC (1997). For most countries we assumed that this fraction remained constant over time.

The methodology used for the calculation of CH_4 emissions from landfills in EDGAR 3.2 is a *first order decay model* resembling the description in the *Revised 1996 IPCC Guidelines* of the more complex Tier 2 method, taking into account that the generation of methane from landfills is not an instantaneous process. Thus, the methodology calculates emissions in a specific year as the sum of delayed emissions from all MSW deposited in past years. A 40-year integration period was used, assuming that emissions from MSW deposited more than 40 years ago are negligible:

$$\text{Methane generated } G(t) = \sum_{y=1}^{40} D(y) * k * L_0 * N * e^{-k\,(t-y)}$$

where:

G(t) = CH_4 generated in year *t* [Gg/yr]

D(y) = $MSW_{Tot}(y) * MSW_{Fr}(y)$ [Gg/yr]

k = methane generation rate constant = ln 2 / HL [1/yr], where HL = Half Life value

L_0 = methane generation potential = $MCF*DOC(t)*DOC_{Fr}*F*16/12$ [Gg CH_4/Gg waste]

N = normalisation factor = $(1 - e^{-k})/k$; to ensure that the sum of years gives the correct value of the methane generation potential L_0.

Here the D(y) components and the methane generation potential L_0 factors are defined as:

$MSW_{Tot}(y)$ = total MSW generated [Gg/yr]

$MSW_{Fr}(y)$ = fraction of MSW disposed to landfills [fraction]

MCF = Methane Correction Factor [fraction]

DOC(t) = Fraction of *Degradable Organic Carbon* in MSW [Gg C/Gg waste]

DOC_{Fr} = Fraction of DOC ultimately dissimilated (excluding lignin C)

F = Fraction of CH_4 in landfill gas.

As region-specific fraction MSW_{Fr} of total MSW or of urban MSW disposed to landfills we used fixed country-specific values for OECD countries from IPCC (1997), except for the USA and for the Netherlands, Germany and Denmark, where we used decreasing fractions for 1970-1995 and 1985-1995, respectively. For EIT, Latin America and other LDC countries we used 95%, 90% and 50% of the urban MSW, respectively, except for India where we assumed a fraction decreasing from 80% to 70% for the 1970-1990 period (Oonk, pers. comm., 2000).

Many other parameters, such as the fraction of Degradable Organic Carbon (DOC), were also based on the *Revised 1996 IPCC Guidelines* (IPCC, 1997). In addition, many others were estimated through consultation of experts (Olivier *et al.*, 2001). For k we used 0.1 as default value; k = 0.05 was used for Southern Europe, Northern Africa, Middle East and Australia, whereas k = 0.15 was used for the rest of the less developed countries except for South Africa and Eastern Asia. In practice k values can vary between 0.005-0.4 year (UNEP, 1999; Oonk, pers. comm., 2000). To investigate the sensitivity of the emissions to the k values used, we compared emissions calculated with global k values of 0.05 with results when using the values of 0.03 and 0.1 and with somewhat different MCF values. Compared to the base case, the emissions changed ±40% in 1970 and ±25% in 1995.

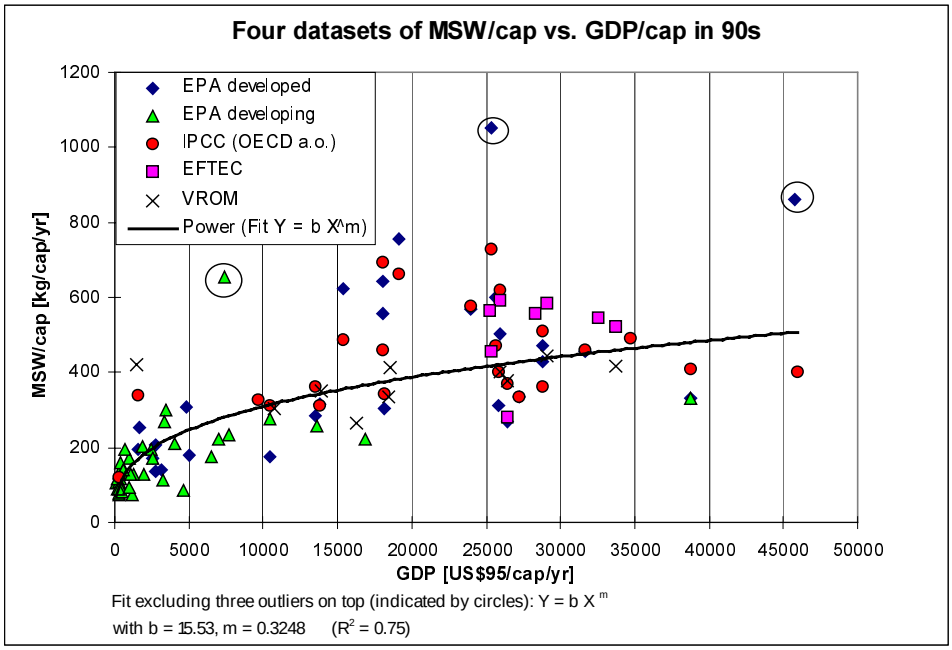

Figure 8. IPCC, EPA, EFTEC and VROM datasets for MSW/cap vs. GDP/cap (US$95) in 1990 for individual countries and power fit to to $Y = b*X^m$.

For MCF we used for OECD'90 countries a fixed value of 1, except for Japan (0.3), France and Australia (0.8) and the rest of Southern Europe (0.7). For EIT and LDC countries we used a MCF value of 0.5, except for EIT and most Latin American countries where we assumed an increase of MCF from 0.5 to 0.7 from 1985 to 1995. For the DOC fraction we used country-specific values provided in IPCC (1997); for other countries we used the value of 0.15, except for Asian countries (0.1) (Oonk, pers. comm., 2000). For DOC_F we used the value of 0.77 (IPCC, 1997) and for F the value of 0.55, which differs from the IPCC (1997) default of 0.5 but complies with the update provided in IPCC (2000).

To calculate actual emissions in year *t*, the methane generated in the landfill should be corrected for (a) any amount recovered *R* (e.g. used energetically or flared) and (b) the fraction of methane *OX* oxidised in the upper layers of waste and in the site cover material, before it is released to the atmosphere. We assumed that default the amount recovered is zero and the oxidation factor is 0 for OECD'90 countries and 0.1 for EIT countries (the IPCC default is 0). Based on national reports submitted to the Climate Convention we included methane recovery amounts for eight OECD countries (Table 3). Table 4 shows how the amounts of waste annually stored in landfills has increased over time but started to decrease in the 1990's in the USA and in the countries of the former USSR. The resulting global trend of associated methane emissions for the period 1970-1995 is presented in Figure 9. According to our analysis, globally the net methane emissions from landfills increase from 15 Tg in 1970 and almost level off at 23 Tg in 1995. This trend includes the effect of increasing amounts of methane being recovered and combustion for energy purposes or flared, which increased from virtually 0 in 1970 to 2.5 and 4.3 Gg in 1990 and 1995, respectively, about half of which was allocated to the USA (Table 3).

Table 3. Methane recovery from coal mining, landfills and wastewater treatment plants (WWTP) (in Gg)

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Coal mining	**0.0**	**0.2**	**0.4**	**0.6**	**0.7**	**0.7**	**0.9**	**1.0**	**1.1**	**1.0**	**1.0**	**1.0**	**1.4**	**1.7**	**2.1**	**2.2**
USA	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.5	0.7	0.8
OECD Europe	0.0	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.3	0.3	0.3	0.4	0.4	0.3	0.3
Oceania	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
Eastern Europe	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2
Former USSR	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
East Asia	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.4	0.4
Landfills	**0.1**	**0.3**	**0.5**	**0.6**	**0.9**	**1.1**	**1.3**	**1.5**	**1.7**	**1.9**	**2.5**	**2.7**	**3.1**	**3.4**	**3.8**	**4.3**
Canada	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3
USA	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.2	1.4	1.6	1.8	2.1	2.4
OECD Europe	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.1	1.1	1.2	1.4	1.4	1.5
Oceania	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
WWTP	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.7**	**0.7**
Canada	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
USA	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3
OECD Europe	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3
Oceania	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Japan	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Grand total	**0.7**	**1.1**	**1.4**	**1.8**	**2.2**	**2.4**	**2.8**	**3.2**	**3.4**	**3.6**	**4.1**	**4.4**	**5.1**	**5.8**	**6.5**	**7.1**

Sources: coal mining: Bibler *et al.* (1998); landfills, WWTP: National Inventory Reports to UNFCCC; Strogies, 2001, pers. comm.

Figure 9 clearly shows the impact of reduced dumping and methane recovery on emissions from the USA in the early '90s with decreasing emissions after peaking around 1990. South America shows an increasing growth rate of emissions since the late 1980s mainly due to an assumed increase of the MCF from 1985 to 1995. In contrast with many other emission sources, the countries in Eastern Europe and the former USSR do not show decreasing landfill emissions in the 1990-1995 period since we assumed that in these regions - like in South America - the Methane Conversion Factor increased in the period 1985-1995 from 0.5 to 0.7.

Table 4. Amount of waste annually stored in landfills per region 1970-1995 (in Tg)

Region	1970	1975	1980	1985	1990	1995
Canada	9.2	10.5	11.6	12.6	13.8	14.7
USA	82.5	96.9	112.9	117.7	121.3	110.8
OECD Europe	82.5	88.6	94.4	97.8	104.4	107.8
Oceania	6.6	7.5	8.0	8.8	9.5	10.5
Japan	38.6	43.4	48.0	51.8	56.6	58.4
Eastern Europe	11.6	13.3	15.1	16.2	16.8	16.8
Former Ussr	31.9	36.9	42.2	46.5	50.9	44.2
Latin America	30.8	38.9	48.1	54.0	61.4	70.4
Africa	7.6	9.4	11.6	14.0	17.0	20.2
Middle East	5.9	7.5	9.0	11.2	13.4	15.4
South Asia	7.1	8.4	10.1	12.2	14.9	18.2
East Asia	10.6	13.2	17.5	24.1	32.7	44.5
Southeast Asia	3.0	3.9	5.1	6.5	8.5	11.1
Global total	328	378	434	473	521	543

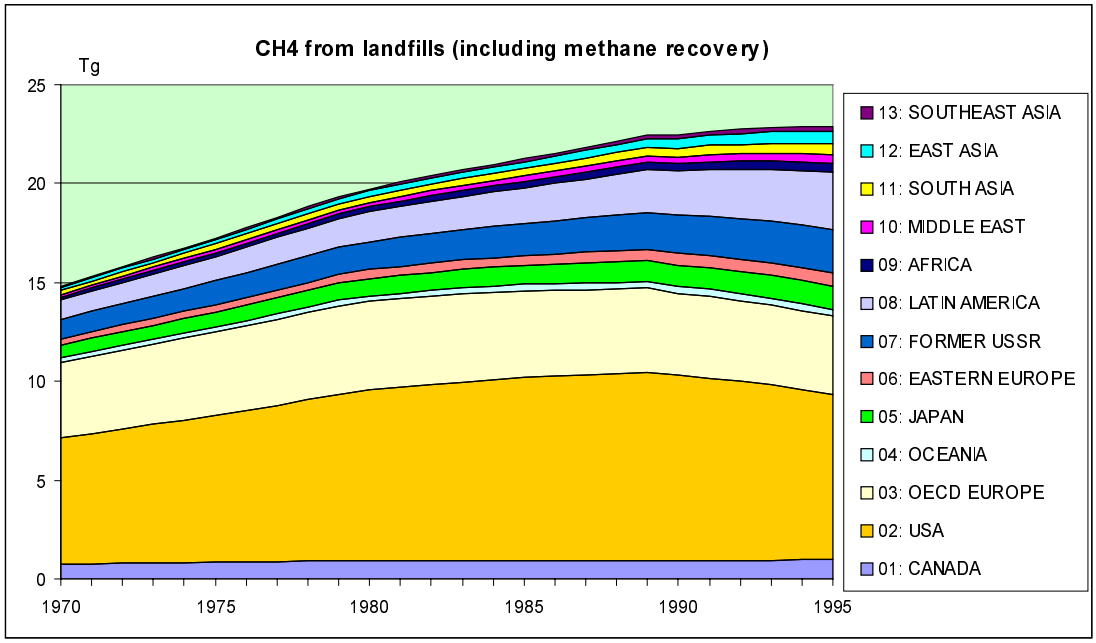

Figure 9. Trend 1970-1995 in net methane emissions from landfills using a first order decay model (including methane recovery).

3.3.2. Wastewater disposal

For domestic and industrial wastewater discharged in city sewers and subsequently treated by municipal Waste Water Treatment Plants (WWTP) we adopted the methodology based on per capita organics loading and industrial waste water generation, respectively, by Doorn *et al.* (1997) since information on domestic wastewater generation rates are very sparse and because this methodology complies with the default IPCC methodology (IPCC, 1997). Doorn *et al.* (1997, 1999) concluded that domestic and industrial wastewater disposal, in particular latrines, septic tanks and open sewers, contributes substantially to global methane emissions.

As activity data for domestic wastewater the population data from the UN (1999) were used. Industrial wastewater generation was based on production of meat, alcohol (methyl and ethyl), raw sugar, pulp and organic chemicals using FAO and UN production statistics (FAO, 2000; UN, 1998). The industry production statistics were combined with waste water generation rates of Doorn *et al.* (1997) of 13, 24, 9, 162 and 67 ton/ton, respectively.

Emission factors for CH_4 from untreated domestic wastewater in latrines or open pits and septic tanks and from stagnant open sewers (untreated wastewater) were based on Doorn *et al.* (1999) following the same approach as for domestic WWTPs, but distinguishing national population into three population groups: rural and urban, with urban population further split into high and low income groups. For each of the four municipal wastewater disposal types, region- and country-specific utilisation fractions were estimated for each of these three population categories. The emissions from open sewers were increased by 25% to account for the global amount of industrial wastewater annually discharged in municipal sewers. To derive country-specific emission factors, region-specific and sometimes country-specific values were used of amounts of high organic loading of chemical oxygen demand (COD) and the fraction of wastewater treated anaerobically (TA_c). The TA_c values were estimated from country-specific values for septic tanks, latrines, open sewers and wastewater treatment in urban and rural areas following the methodology and assumptions of Doorn *et al.* (1997).

In addition, several national greenhouse gas inventories reports of OECD countries, which cover about 60% of the reported total of this source, mention a methane recovery rate of about 75% for their with wastewater treatment plants. Therefore we tentatively assumed a 75% methane recovery for municipal WWTPs in OECD'90 countries, effectively reducing the total emissions of OECD countries in 1990 by 0.6 Tg. According to this dataset, the emissions from waste water disposal and treatment increased from 19 to 33 Tg/yr in the period 1970-1995, with 85% stemming from waste water disposal, i.e. from latrines, septic tanks and open sewers (Figure 10). Globally, following the assumptions of Doorn *et al.* (1999), this source of methane appears to be as large as global emissions from landfills.

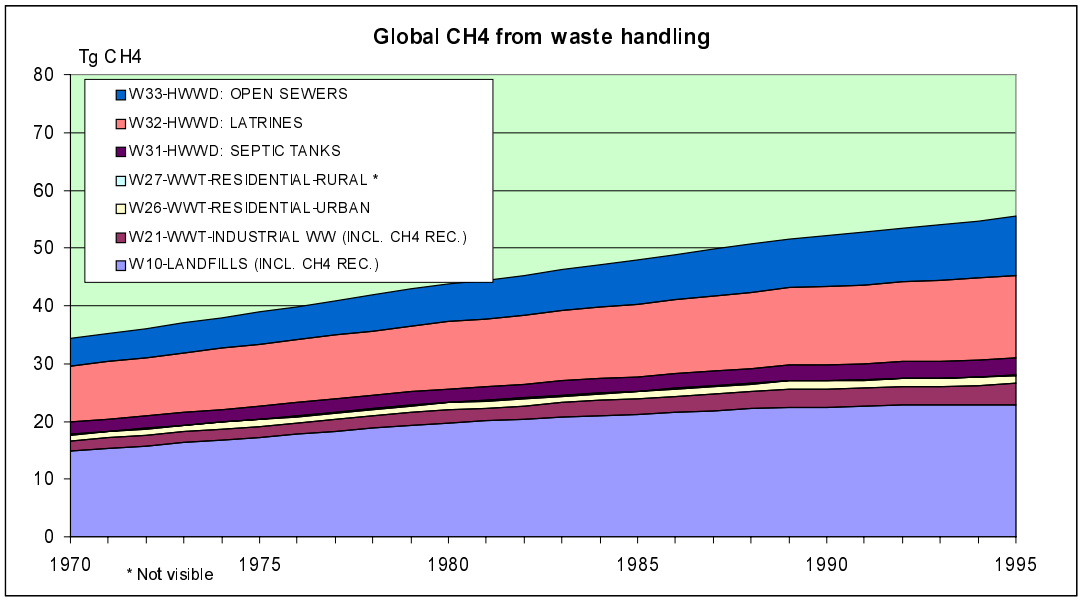

Figure 10. Global methane emissions 1970-1995 from waste handling: landfills and domestic and industrial wastewater disposal (latrines, septic tanks, open sewers) and treatment (including methane recovery).

3.3.3. Other solid waste handling

For the small source of domestic waste burning (by households for non-energetic purposes) we tentatively assumed a fixed amount of 10 kg per urban capita burned per year by *urban households* in less developed countries, adopted from Gupta *et al.* (1998). In rural areas of LDC we assumed no uncontrolled burning in addition to the agricultural residue burning and biofuel use that is already accounted for in other source categories. In contrast, for industrialised countries, we assumed that domestic waste burning only occurs in rural areas, where waste incineration regulation is less well controlled. As emission factor we used the factor for vegetal biofuel (agricultural waste) (see Table 1). Global total methane emissions are estimated at about 1 Tg/yr.

3.4. Large-scale biomass burning

Biomass burning data for large-scale vegetation fires in the tropics were based on FAO reports providing 10-year or 5-year averaged estimates per country of the change in forested areas for the 70's, 80's and the first half of the 90's (FAO, 1993, 1995, 1998a). Following the methodology described in the *Revised 1996 IPCC Guidelines* (IPCC, 1997), these data were used as a proxy for estimating the amount of biomass being burned in forests in tropical countries, since there is no time-series data per country on this subject readily available. To construct a continuous time series per country for the 1970-1995 period we used the following smoothing procedure:

a) the 1990 level was chosen to be 2/3*90s-average + 1/3*80s-average;
b) the linear trend 1990-1995 was determined by the condition that the 90-95 average should equal the FAO figure for that period;
c) the linear trend 1980-1990 was determined by the condition that the 80-90 average should equal the FAO figure for that period;
d) for the period 70-80 we assumed the same annual figure as determined for 1980 in (c);
e) for years where this procedure resulted in negative values, the area was set to zero.

We tentatively assume that all 50% of the biomass removed is burned. Given the uncertainty in this figure we assumed that the fraction oxidised is 1. For OECD'90 and EIT countries, temperate forest fire statistics for 1986-1997 have been included based on UN/ECE statistics of annual area burned (UN-ECE/FAO, 1996) combined with forest biomass densities per hectare from FAO (1995).

For savannah burning we also followed the IPCC (1997) approach for estimating the area and amount burned in 1990: total savannah area per tropical country was calculated as total forest area minus closed broadleaved forest from FAO (1993) plus for other wooded land from FAO (1995). In addition we added for Australia 240 Tg dry matter (dm) area of savannah burning estimated by Hurst *et al.* (1996). Other regional parameters used in the calculation, such as the frac-

tions of area and biomass annually burned and above-ground biomass density, were according to IPCC (1997) and Hurst *et al.* (1996), respectively. The IPCC (1997) data are based on Hao (1990) and for non-tropical Africa on Menaut *et al.* (1991). The fraction oxidised was assumed to be 1 for dead biomass and 0.8 for live biomass (IPCC, 1997). For the 1970-1995 trend in savannah burning we used the land-use change results of the IMAGE 2.1 Baseline A simulation (Leemans, 1998). This simulation started in 1970 and was calibrated to observed 1990 data. For all regions the models calculates decrease of the order of 5 to10%, except for East Asia where the landuse model calculates a strong decrease of 75% in the period 1970-1990 and of 50% over the years 1990-1995.

Temperate vegetation fire area for Europe, North America, Asia, Japan and Oceania were combined with forest biomass densities per hectare from FAO (1995), supplemented with national data for Australia (AGO) and Mongolia (GVFI). Figure 11 clearly shows that the interannual variability of the amounts of biomass burned is very large, indicating that our 'smoothed' approach for tropical forest fires is a very synthetic one.

For large-scale biomass burning the emission factors for CH_4 were also based on IPCC (1997), except for CH_4 from tropical deforestation and temperate vegetation fires, where we used the GEIA value proposed by Veldt and Berdowski (1995) (see Table 5).

We emphasise that in particular for tropical and temperate forest fires the uncertainty in the assumption for the biomass density and the fraction of carbon actually burned (0.5), and thus in the amount of burned carbon, is very large. The area data selected from FAO sources, although often criticised for its limited accuracy, is however well known and relatively well documented. Moreover, the resulting global CO_2 emissions from tropical forest fires in 1990 of 1.9 Pg CO_2/yr are in line with other estimates.

3.5. Industrial non-combustion processes

For this minor source category we used production data of pig iron, sinter, ethene and styrene based on UN Industrial Commodity Statistics (UN, 1998). However, for many countries interpolations and extrapolations were necessary to arrive at complete time series per country for 1970-1995. Special attention had to be given to new EIT countries, in particular to former SU countries, to match the older totals for the former countries. Global emission factors as in EDGAR 2 were used: 900, 500, 330 and 30 kg CH_4 per kiloton of pig iron, sinter, ethene and styrene, respectively (Builtjes, 1992). These are different from IPCC defaults which are 1000 and 4000 for ethene and styrene, respectively. Global total methane emissions are estimated at about 1 Tg/yr.

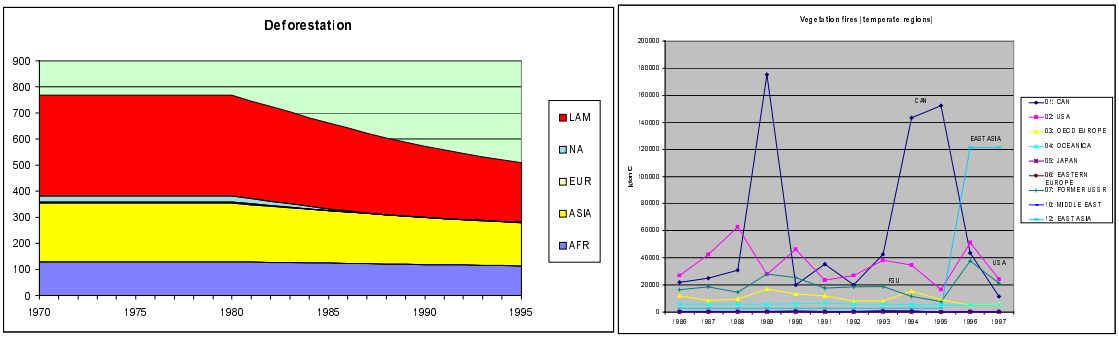

Figure 11. Resulting trend in annual area burned by forest fires: 'smoothed' tropical deforestation (Tg C oxidised) (left); large interannual variation of vegetation fires in temperate regions (Gg C oxidised) (right).

Table 5. Emission factors for biomass burning in EDGAR 3.2 (g/kg C)

Compound	Deforestation	Savannah fires	Agric. Waste	Temperate vegetation fires	Fuelwood	Fuelwood
	(g/kg C)	(g/kg C)	(g/kg C)	(g/kg C)	(g/kg C)	*(g/GJ)*
CO_2	3667	NA	NA	3667	367 [1)]	*1)*
CH_4	10	5.3	6.7	10	6.8	*300*
N_2O	0	0.07	0.165	0.22	0.08	*4*
CO	200	133	133	300	64.3	*5000*
NMVOC	10	9	16	40	13.5	*600*
NO_x	4	7.9	6.0	12	1.4	*150*
NH_3	1.85	1.85	1.85	1.85	1.4	*55*
SO_2	1.4	1.4	1.4	1.4	0.2	*15*

[1)] 10% of C content, comparable with an unsustainable production of 10% (reference value, to indicate order of magnitude).

3.6. Natural sources

Wetlands have been identified as probably the largest natural source of methane. However, its source strength is highly uncertain due to various reasons: (a) definition issues, e.g. permanent versus seasonal wetlands, (b) soil types, e.g. boreal bogs/tundra versus swamps in tropical regions, (c) forested vs. non-forested land, (d) other characterisation of grid cells in global datasets, e.g. inundation fractions (Matthews and Fung, 1987; Matthews, 2000). This causes total wetland area, a key parameter, to be very uncertain. Intercomparison of six different estimates in Darras *et al.* (1999) suggests that even the compilation of Matthews and Fung (1987) of 5.2 mln km^3, which is towards the high end of the group range, could largely underestimate actual total wetland area. Our estimate of wetland emissions for boreal areas is in line with Fung *et al.* (1991). For tropical swamps we assume a value of 100 Tg/yr. This value is just between the original 35 Tg/yr estimated by Matthews and Fung in the late 1980s and the much higher recent estimates of about 190 Tg/yr by Crutzen *et al.* (1995) and Hein *et al.* (1997) (see Table 6). The total source strength for wetlands of around 180 Tg/yr is well in the range of published top-down inferred values such as inverse modelling studies by Hein *et al.* (1997) and by Houweling *et al.* (1999). Our figure accounts for about 60% of the high bottom-up estimate of 263 Tg/yr net emissions recently published by Walter *et al.* (2001a,b). Moreover, our assumptions on wetland emissions, in particular for tropical regions, comply with a total global source strength of all sources of well over 500 Tg/yr, since our anthropogenic estimate is – particularly in tropical regions – lower than most previous estimates (Table 6) due to our lower estimate of rice emissions.

Termites are another natural source often cited in the literature also with very high uncertainty ranges of 0 to 200 Tg/yr. However, since two independent bottom-up studies both give 20 Tg/yr as best estimate (Fung *et al.*, 1991; Sanderson, 1996), we also adopted this value. In addition there is a variety of other small natural sources, of which oceans and hydrates were already mentioned by Fung *et al.* (1987). A review of available literature (Olivier, 2000) showed that methane from oil and gas seepage from continental shelves as well as from the surface of the continents could be quite high. However the total fossil fuel source is rather well constrained to a range of about 80-130 Tg/yr (Fung *et al.*, 1991) by isotopic information on the atmospheric ratio of $^{14}C/^{12}C$ ($\delta\ ^{14}C$) of methane. In view of our estimate of anthropogenic methane emissions from fossil fuel of about 90 to 95 Tg/yr in the 1990s, we assume this source rather small (about 5 Tg/yr) for the time being. In addition, we add two times 5 Tg/yr for emissions from wild animals and (average) emissions from volcanoes as estimated by Houweling *et al.* (1999). This brings our estimate for total natural emissions at 230 Tg/yr and total sources at about 530 Tg/yr, which is in line with published budgets for the late 1980s and the 1990s (Table 6). These budgets also assume a terrestrial sink of about –30 Tg/yr through oxidation in dry soils (dry deposition), and stratospheric sink of about –40 Tg/yr. Chemical destruction in the troposphere by OH is estimated by the models at about –450 to –500 Tg/yr.

Finally, we want to stress that wetland emissions are very sensitive to weather conditions, in particular temperature and precipitation amongst other through their influence on the soil temperature and the water table, respectively. Walter *et al.* (2001b) show that their process-based model studies indicate that a 1°C temperature change or 20% change in precipitation globally would lead to a change in global emissions of the order of 20% and 8%, respectively. They analysed the interannual variability in the period 1982-1993 and conclude that the wetland emissions show a high degree of regional, seasonal and interannual variability.

3.7. Supplementary data sources

In order to allocate per country emissions to a 1x1 degree grid, source-specific grid maps were used for each source as was done for EDGAR 2.0. For a complete list we refer to Olivier *et al.* (1996, 1999). Most of these maps were compiled for the activities in years around 1990. As mentioned above, we used the same maps as proxy for all years in the 1970-1995 period. However, for EDGAR 3 some have been replaced by improved maps:

- rice production in Asia (Denier van der Gon, 2001, pers. comm.) and IMAGE rice production maps for other regions;
- population distribution, split into urban and rural population, based on a new GEIA total population map (Li, 1998);
- steel production by process type, covering a large part of coal/coke combustion in the industry sector (also used for locating coke ovens);
- coal fire map for China and other countries.

For methane emissions the urban and rural population maps are particularly important for allocating the waste handling emissions. Details on how these maps were constructed are provided in Olivier *et al.* (2001).

4. Results and comparison with other studies

4.1. Results

The results of the new dataset can be analysed in terms of totals and shares of sources and regions for specific years and in terms of the trend in the 1970-1995 period. In Appendix A, resulting emissions per main source

category are presented per region for 1970, 1980, 1990 and 1995. At global level the largest source categories are agriculture, fossil fuels, and waste handling, contributing about 45%, 30% and almost 20% to the global anthropogenic total in 1995, respectively. Within the agricultural sector, enteric fermentation by ruminants is by far the largest source, followed by rice cultivation. Within the waste sector, surprisingly the analysis made for the waste sector based on methodology and assumptions by Doorn *et al.* (1997, 1999) leads to conclude that landfills and domestic and industrial wastewater disposal (latrines, septic tanks, open sewers, and wastewater treatment plants) appear to contribute about the same as landfills to global methane emissions. Within the fossil fuel category coal production and gas transmission are the largest sub-sources (Figure 2). The regions contributing most to the global total in 1995 are East Asia with 16% and followed by South Asia, USA, Latin America and the former USSR, each contributing 12% to 14%.

Figures 12 and 13 show the global total trend of anthropogenic sources and regions, respectively. The most striking feature in the dataset, the 20% increase from about 250 Tg CH_4/yr in 1970 to 300 Tg CH_4/yr in 1995, was primarily caused by the following source trends: gas production and transmission (+12 Tg each),

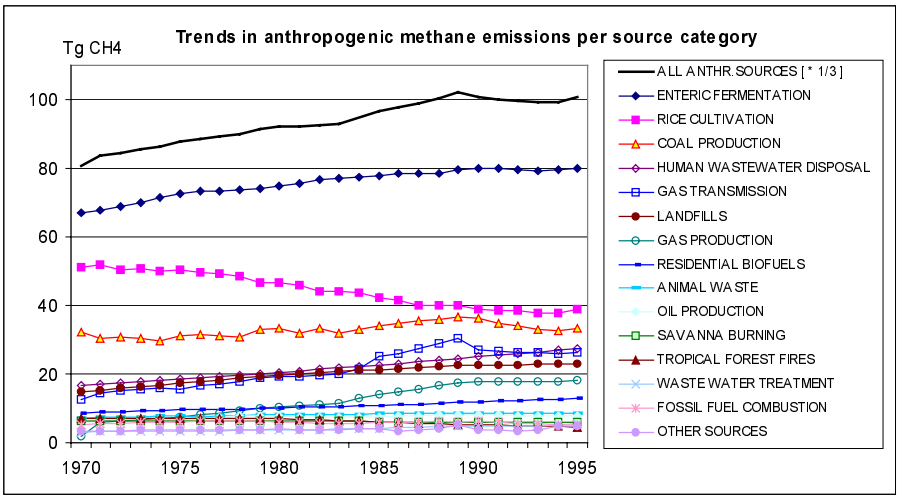

Figure 12. Trend in global emissions of methane by source category 1970-1995.

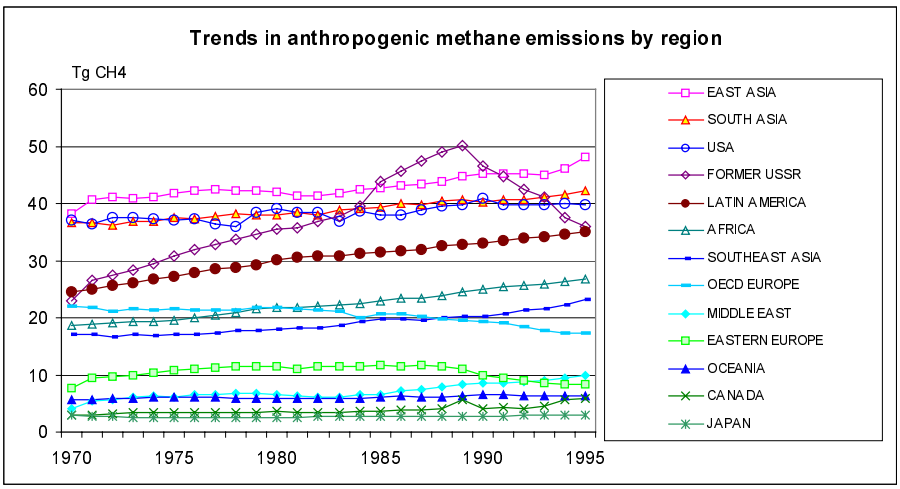

Figure 13. Trend in anthropogenic emissions of methane by region 1970-1995

enteric fermentation by animals (+13 Tg), human wastewater disposal (+11 Tg), landfills (+8 Tg), whereas our analysis indicates a 15 Tg decrease in emissions from rice production. The increase would have been 3% higher, without the methane recovery in landfills (4 Tg) coal mining (2 Tg), and WWTPs (1 Tg). Geographically the increase was more evenly spread, which the largest increases having occurred in Latin America and the former USSR (+10 Tg each), followed by East Asia and Africa (+8 Tg each) and Southeast and South Asia and the Middle East (+5 Tg each), while the emissions in OECD Europe decreased in this period by almost 5 Tg. In the '80s the global anthropogenic emissions increased by about 10%, predominantly due to increases in former USSR resulting from the strong increase in gas production and transmission. In addition, also enteric fermentation by ruminants and wastewater disposal, in particular in less developed regions, contributed to this growth trend. In particular in the case of methane, the declining economy of the former USSR countries in the early 1990's had a large impact on the global trend in methane emissions: emissions from coal and gas production dropped substantially between 1990 and 1995 (Figure 2). It should be stressed, however, that statistics for this region are rather uncertain in this period. Also methane emissions from coal production have decreased substantially within OECD Europe as a result of the policies of Germany and the UK to reduce domestic coal production over time (see Figure 2). As a result, increasing emissions from the waste handling sector, in particular in Asia, were compensated causing global total methane emissions to stabilise during the early '90s.

Our results indicate that in 1995 the largest sources are fossil fuel production/transmission and animals (both 30%), waste handling (18%) and rice production (13%). According to our estimates five countries cover 50% of global total 1995 anthropogenic emissions: China (15%), USA (13%), India (10%)., the Russian Federation (8%) and Brazil (5%). Five more countries add another 10%; the top 20 countries cover almost three-quarters of the global total. These countries clearly show as 'hot spots' when looking at the gridded emissions in 1995 (Figure 14).

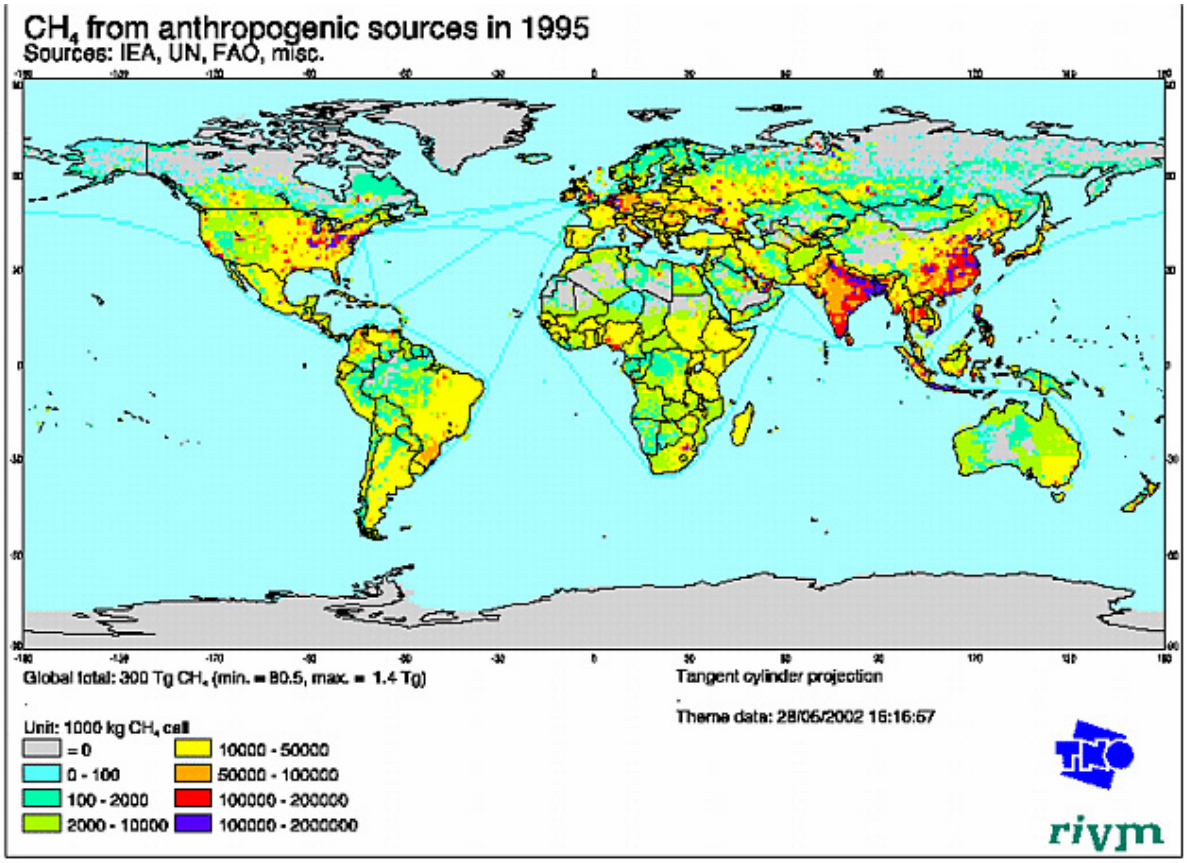

Figure 14. Spatial distribution of anthropogenic emissions of methane in 1995.

4.2. Comparison with other studies

We have compared our results with other studies, however most of them are not bottom-up inventories, but rather combinations of anthropogenic and natural source and sinks estimates by atmospheric modellers (Table 6). These estimates are often based on other studies. Combined they fit global budgets of sources, sinks and atmospheric increases. They are either used as 'a priori' estimates or they represent selected results of inverse modelling. Exceptions are the bottom-up study for the mid 1980s by Fung *et al.* (1991) and the EDGAR 2.0 inventory for 1990 by Olivier *et al.* (1999). The most striking differences with the other studies are our rice and biomass burning emissions, which are the lowest of all studies.

Our estimate for rice is at the lower end of the estimated uncertainty ranges. The differences in our estimate for total emissions from all sorts of biomass burning are not caused by large differences in the total amount. This is rather due to different estimates for the components: tropical forest fires, savannah burning, biofuel use and agricultural waste burning, and due to different emission factors, which are somewhat lower than used by others (except for agricultural waste, but these are assumed to be a minor source). Our estimate for waste handling is higher than most other studies, which is not due to our estimate for landfill emissions – which are in fact lower than the other estimates – but to the addition of wastewater disposal and treatment as a substantial source of methane. Since most of the wastewater emissions are assumed to stem from latrines and open sewers, predominantly in high population areas of developing countries, these emissions may more or less compensate our lower methane emissions from rice producing countries. As discussed in Section 4.6, we assume natural sources, notably wetlands, to be higher than the early estimates made in the late '80s/early '90s. When we compare our new EDGAR 3.2 estimates for 1990 with those of EDGAR 2.0, key differences are:

- wastewater treatment has been added, which is a substantial source of CH_4;
- emissions from landfills and rice cultivation are much lower, due to a complete revision of emission factors;
- agricultural waste burning emissions have been decreased substantially, due to lower fractions assumed to be burned;
- animal emissions have decreased somewhat due to a refined calculation of animal waste emissions.

These and other smaller changes caused a decrease in our estimate of global total anthropogenic emissions in 1990 of 19 Tg from 321 Tg to 302 Tg.

Next, we consider the 1970-1995 trend estimate in the EDGAR 3.2 dataset. To our knowledge there is no other detailed bottom-up study published on the trends in global total methane emissions. However, our calculated increase of about 50 Tg in this period is confirmed in a study based on atmospheric concentration measurements by Khalil and Rasmussen (1994) and in an inverse modelling study by Dentener *et al.* (2002). In recent literature, speculations were made about the causes of three phenomena: (a) the declining growth rate in atmospheric methane concentrations, suggest almost constant emissions in the period 1984-1997; (b) the strong negative growth rate anomaly in the northern hemisphere in 1992; and (c) a strong positive anomaly in 1991. These anomalies correspond to interannual changes of global emissions of about 10 to 20 Tg CH_4, respectively (Dlugokencky *et al.*, 1998). Our bottom-up results indicate a halt in global anthropogenic emission growth from 1988 onwards. Figure 12 clearly shows that the total emission trend is a delicate balance of the sum of many source trends, some of them are declining (rice, agricultural waste burning in Europe, tropical forest fires), others are increasing (animals, wastewater) and some are stabilising (coal mining, landfills). However, there was one rather abrupt change in human activities in the late 80s/early 90s, which is the change of the Soviet Union and the Eastern European countries into so-called 'Economies In Transition'. The statistics available for these countries show large decreases sometimes of the order of 50% in a few years time for almost all activities, ranging from coal, gas and oil production and consumption, animal numbers to waste generation. This has had a substantial effect on global emissions as can be clearly observed in the data. Global total coal mining emissions remained more or less constant in the '80s and '90s (Figure 2) due to the global shift towards more surface mining and increasing amounts of methane recovered from coal mines (and combustion for energy purposes or flared) (Table 3).

Table 6. Comparison of EDGAR 3.2 with other emission inventories, including original bottom-up studies by Fung *et al.* (1991) and EDGAR 2.0

Reference [8]	FU91		MA94		CR95		HE97		HE97		OL99		HO99		This study			
Year [total sources]	1980s	[500]	1990 [2]	[500]	- [3]	[640]	83-89 [4]	[575]	91-93 [5]	[588]	1990 [6]	(321)	1990 [7]	[559]	1985	1990	1995	[532]
Anthropogenic sources:	350		350		370		343		351		321		370		289	302	302	
Energy	75		75		100	82-118	103	88-118	98	82-112	95	70-120	95		88	96	92	
- *Coal mining*	*35*	*25-40*	*35*	*35-60*	*35*	*25-45*	*33*	*23-43*	*35*	*25-45*	*38*	*19-57*	*38*	*23-52*	*34*	*36*	*33*	*18-54*
- *Gas production/transm.*	*10*	*10-80*	*10*	*10-15*	*20*		*34*	*21-47*	*17*	*3-31*	*18*	*9-27*	*51*	*31-81*	*14*	*18*	*18*	*9-27*
- *Gas distribution*	*30*	*15-40*	*30*	*30-50*			*36*	*13-59*	*46*	*23-69*	*26*	*13-39*			*25*	*27*	*26*	*14-40*
- *Oil / misc.*					*45*						*13*	*6-19*	*6*	*2-10*	*14*	*15*	*14*	*7-22*
Animals	80		80		110	88-132	90	70-110	90	70-110	93	45-140	93	58-128	86	89	89	45-135
Rice	100	50-110	75	50-	80	20-140	69	46-92	88	68-108	60	30-120	80	30-130	42	39	39	20-80
Biomass burning	55	50-100	55	20-75	40	20-60	41	30-42	40	28-52	37	25-50	54	10-95	25	26	27	10-50
Waste handling	40		65		40		40		35		36		48		48	52	56	30-80
- *Landfills*	*40*	*15-40*	*25*	*25-70*	*40*	*20-60*	*40*	*25-55*	*35*	*20-50*	*36*	*15-75*	*48*	*28-68*	*21*	*22*	*23*	*7-40*
- *Wastewater*			*40*	*0-?*											*27*	*30*	*33*	*10-50*
Natural sources:	150		150		270		232		237				188.5		230	230	230	
Wetlands	115	80-115	115	100	270	220-320	232	205-259	237	217-257			145		180	180	180	100-
- *bogs/tundra (boreal)*	*80*		*80*		*100*		*44*	*36-52*	*44*	*37-51*			*54*	*39-69*	*80*	*80*	*80*	*40-100*
- *swamps/alluvial*	*35*		*35*		*170*		*188*	*163-213*	*192*	*173-211*			*91*	*65-117*	*100*	*100*	*100*	*60-150*
Termites	20	15-100	20	0-200									20	0-40	20	20	20	0-100
Other	15		15										23.5		30	30	30	15-65
- *Oceans*	*10*	*10-15*	*10*	*0-20*									*10*	*5-15*	*10*	*10*	*10*	*5-15*
- *Hydrates*	*5*	*0-5*	*5*	*0-10*											*5*	*5*	*5*	*0-10*
- *Seepage*													*5*	*0-10*	*5*	*5*	*5*	*0-30*
- *Volcanoes*													*3.5*	*0-6*	*5*	*5*	*5*	*0-6*
- *Wild animals*													*5*	*0-10*	*5*	*5*	*5*	*0-10*
Sinks:	-460		-460		-550		-541		-535									
Soil oxidation (dry soils)	-10		-10		-30	-15/-45	-28	-14/-42					-30					
Chemical destruction by OH	-450		-450		-480	-384/-576	-469	-439/-499	-489				-451	-429/-473				
Stratosphere					-40	-32/-48	-44	-36/-52	-46				-37	-27/-47				

[1] Scenario 7; uncertainty estimates derived from paper. Compared with 84-87 concentrations.
[2] Uncertainty estimates from cited literature ranges.
[3] As cited in Hein *et al.* (1997). 20 Tg gas is Siberian gas only; rest of gas has been included under misc(ellaneous).
[4] Scenario S1, using CR95 as *a priori* budget.
[5] Scenario S5, using CR95 as *a priori* budget.
[6] Uncertainty ranges converted using S-10%, M-50%, and L-100% and calculated sums for energy and biomass burning.
[7] Biomass burning including 14 Tg biofuels. A priori estimates from OL96/99 and Lelieveld et al. (1998), except OH and stratosphere sinks.
[8] FU91 = Fung *et al.*(1991); MA94 = Matthews and Fung (1991); CR95 = Crutzen *et al.* (1995); HE97 = Hein *et al.* (1997); OL99 = Olivier *et al.* (1996; 1999); HO99 = Houweling *et al.* (1999).

In this analysis we did not include a possible long-term trend in wetland emissions, e.g. due to changes in global climate. We argue that natural sources, together with large-scale biomass burning peaks during El Niño years, e.g. 1972-73, 1976, 1982-83, 1986-87, 1991-1992, 1994-95 and 1997-98, are more important to explain the strong interannual variation of emissions as observed from atmospheric burden measurements. Walter *et al.* (2001a) explain that the 1992 negative emission anomaly is caused by a negative temperature anomaly coinciding with a negative water table anomaly like to be caused by the eruption of the Pinatubo volcano in 1991. We recall that the present EDGAR 3.2 dataset does not capture the interannual variability in tropical biomass burning; instead a 'smoothed' trend function has been used for these sources.

We conclude that our global total of about 530 Tg in 1990 for all sources is to the lower range of the studies presented, but still in line with global budgets in view of the uncertainties estimated for the sinks. Also our source totals, although considered as 'best' estimates using a bottom-up direct estimation approach, are still within most uncertainty ranges of the studies presented in Table 6. The long-term source trend of a 50 Tg increase over the last decades and the levelling trend since the late 1980s does – although perhaps partly accidentally – comply with recent studies of the emission trends by Dlugokencky and Dentener and co-workers. However, the annual anomalies in 1991 and 1992 cannot be captured by our estimates of anthropogenic sources.

5. Uncertainties in annual anthropogenic emissions and in emission trends

We have discussed our strategy in compiling a dataset that covers the most relevant structural changes and changes in emission factors that contribute to the global total trends of anthropogenic methane emissions. Nevertheless, there are a number of key uncertainties and possible biases in the dataset. Most of the uncertainties in the emissions are likely to originate in the uncertainty of the applied emission factors. The basic factors for 1990, though consistent across regions and countries, may be quite uncertain since they were calculated for a simple Tier 1 methodology or using regional source characteristics. Statistics used for basic commercial activity data are usually rather accurate. Most of the uncertainty in activity data shows up in the non-commercial sources: biomass and biofuel burning, but also the amounts of municipal waste disposed in landfills and the amount of untreated wastewater.

We note that for rice production in China and temperate vegetation fires we included corrections for under-reporting or estimates for the biomass density, which are rather uncertainty and maybe at the upper side of the uncertainty range. Finally, additional uncertainty occurs in the source-specific grid maps used to distribute national emissions to the grid cells within the country.

Regarding differences in the uncertainty of the emission factors for 1995 and for 1970 relative to 1995, we refer to the Section 3 where we discussed the data sources per source category. It should be underpinned that in most cases the datasets with evidence of trends in emission factors did not cover all countries and extrapolation to the other countries was necessary. For coal mines, notably information on trends in China were missing, whereas trend information for rice production for the emission factors covered only about 50% of global emissions. In addition, our assumption of emission factors that remain constant in the gas and oil sector in the former USSR, for non-dairy cattle in OECD and EIT regions may be disputed. Our analysis of information on the former USSR, however, did not lead to conclusive judgements on changes in emission factors in the oil and gas industry. Also, the parameters used in calculating emissions from landfills and wastewater can be questioned.

First we estimated the uncertainties in regional and global emissions using an order-of-magnitude estimate in both activity data and emission factors (Olivier *et al.*, 1999). Previously we assigned uncertainties to global and regional emissions per source category based on order-of-magnitude uncertainty estimates for activity data and emission factors (i.e. ±10%, ±50%, ±100% and >100% for the confidence levels 'High', 'Medium', 'Low' and 'Very Low') based on a number of references, supplemented with own estimates based on expert judgement (Olivier *et al.*, 1999, and references therein) (see Figure 15). We observed a fairly similar pattern when we compared our results with the uncertainty estimates presented in the IPCC's synthesis report *Third Assessment Report* (IPCC, 2001), (Olivier and Peters, 2002), which shows that this simple approach and interpretation of uncertainty ranges is useful for application at global levels. Comparison with other uncertainty estimates, for example the ranges presented in Table 6, shows that by and large our uncertainty estimates are in line with other estimates in the literature. Next, we refined this approach somewhat (by including uncertainties of ±5% and ±25% in the set listed above) for a regional assessment (including differences in uncertainty estimates per region).

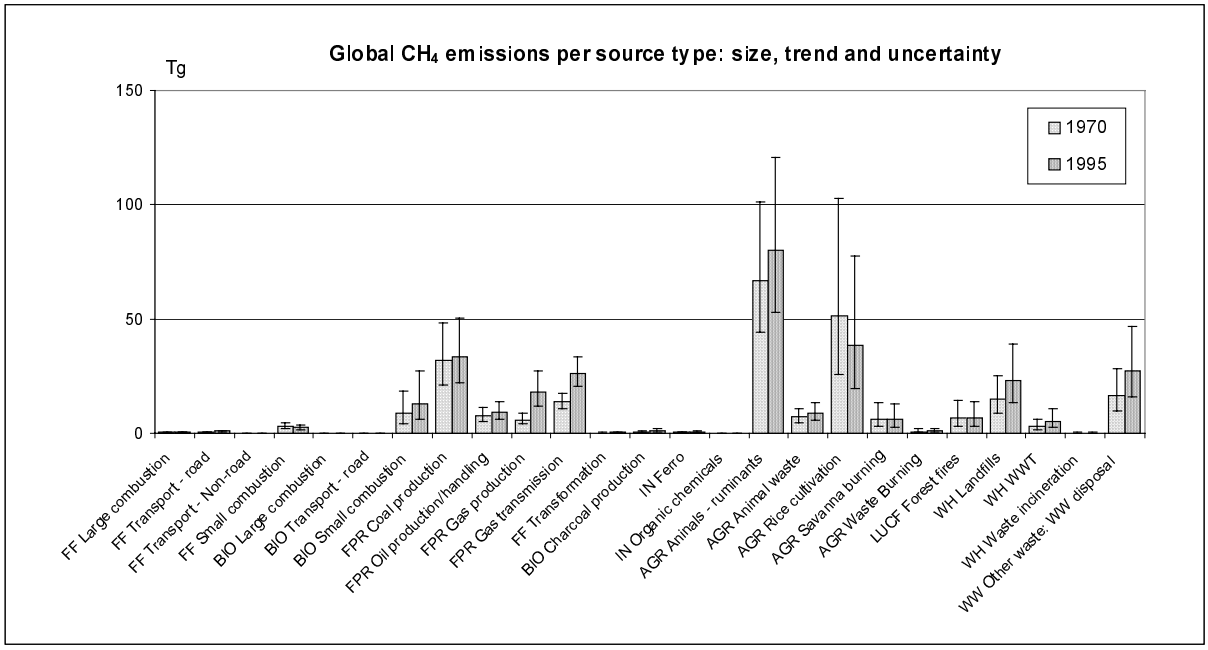

Figure 15. Global anthropogenic methane emissions per source category: size, 1970-1995 trend and annual uncertainty

This was done in view of our judgement of the varying regional quality of activity data and uncertainty in emission factors, both in the start year and end year of the period considered. In the following sections first the uncertainty estimates in annual emissions and in the 25-year trend at global/regional levels are discussed using the uncertainties above and next the uncertainty in annual emissions at country and grid cell levels are discussed in more detail.

5.1. Uncertainties in the global and regional annual totals and 1970-1995 trends

First, our estimates of 'global' uncertainty in activity data and emission factors were used to calculated the total *annual* uncertainty in global total anthropogenic methane emissions in 1995, the results of which are presented in Table 7. In this table also typical uncertainties of input data at global and regional levels can be found, based on expert judgement. We note that that at regional level 'regional averaged' emission factors could contain less uncertainty than at national level due to the averaging process. Next, we estimated the uncertainty in the global *trend* of 22% increase over the 1970-1995 period in global emissions from the anthropogenic sources by applying the IPCC Tier 1 trend uncertainty estimation method, originally developed for individual countries, to our global inventory (IPCC, 2000). Here we used the default assumptions that activity data are uncorrelated and emission factors are correlated between years.

Next, we applied the IPCC uncertainty estimation method to the source totals of three world regions: OECD'90, Economies in Transition (EIT) and less developed countries (LDC). This is a more refined approach where we distinguish different trends and uncertainties for the different world regions. In fact, in analysing the case for the three regions we simulated correlations of emission factors within each region as well as region-specific uncertainties in the underlying data, which were then combined to get the trend uncertainty for the globe. Using these region-specific uncertainty estimates for the three regions OECD'90, EIT and LDC, *annual* and *trend* uncertainty changes only a little bit: annual uncertainty from ±23% to ±21%; the uncertainty in the *trend* increases from ±18% to ±21% points (Table 8). Thus, refining using a – more homogeneous – regional assessment does not substantially change the annual and trend uncertainties. Further investigation may reveal which approach is most appropriate, in view of the correlations identified in this case. Moreover, the uncertainty estimates for the three individual regions are more pronounced when using region-specific uncertainties than when applying global uniform uncertainty estimates per source category. Both annual uncertainty in 1995 emissions and the trend uncertainty vary between about 10% for the OECD region to about 20 to 40% for the LDC region (vs. 20 to 30% in case of global defaults) (Table 8). With a calculated 2% increase in OECD emissions from 1970 to 1995, it is hard to judge whether the emissions of these countries indeed stabilised or that they increased

or decreased up to approximately 10%. From our calculations we draw the following conclusions:

- in the total global the annual uncertainty of 23%, the largest contributors are the categories enteric fermentation by ruminants [IPCC category 4A] and rice cultivation [4C], followed by landfills [6A] and coal mines [1B1] and residential biofuel use [part of 1A4];
- the increasing trend of 22% globally has an uncertainty of ±18% points, the largest contributors are at global level: wastewater disposal [6B], landfills [6A] and rice cultivation [4C], followed by residential biofuel use [part of 1A4] and ruminants [4A];

Table 7. Uncertainty estimate of annual methane emissions and in the 1970-1995 trend: regional approach versus global total

IPCC category	Source description	1970 (Tg)	1995 (Tg)	U_{AD} (unc)	U_{EF} (unc)	U_{EM} annual	contribution to U_{EM} in 1995	(contr. to) U_{EM} trend
1A1,2	FF Large combustion	0.3	0.5	10%	50%	51%	0.1%	0.0%
1A3	FF Transport - road	0.4	0.8	10%	50%	51%	0.1%	0.1%
1A4	FF Transport - non-road	0.0	0.0	10%	50%	51%	0.0%	0.0%
1A4	FF Small combustion	3.0	2.3	5%	50%	50%	0.4%	0.3%
1A1,2	BIO Large combustion	0.0	0.1	100%	50%	112%	0.0%	0.0%
1A3	BIO Transport - road	0.0	0.0	100%	50%	112%	0.0%	0.0%
1A4	BIO Small combustion	8.7	12.8	100%	50%	112%	4.7%	7.3%
1B1	FPR Coal production	32.0	33.4	10%	50%	51%	5.6%	2.2%
1B2	FPR Oil production/handling	7.5	9.2	10%	50%	51%	1.6%	0.5%
1B2	FPR Gas production	5.9	18.2	10%	50%	51%	3.1%	2.5%
1B3	FPR Gas transmission	13.9	26.3	10%	25%	27%	2.3%	1.8%
1B1,2	FTR Transformation	0.3	0.4	10%	50%	51%	0.1%	0.0%
1B1	BIO Charcoal production	0.6	1.0	100%	50%	112%	0.4%	0.6%
2A	IND Iron and steel industry	0.6	0.8	10%	10%	14%	0.0%	0.0%
2D	IND Organic chemicals	0.0	0.0	10%	10%	14%	0.0%	0.0%
4A	AGR Animals - ruminants	66.9	80.1	10%	50%	51%	13.5%	4.6%
4B	AGR Animal waste	7.0	8.5	25%	50%	56%	1.6%	1.2%
4C	AGR Rice cultivation	51.3	38.7	10%	100%	100%	12.9%	9.9%
4E	AGR Savannah burning	6.3	6.0	100%	50%	112%	2.2%	3.4%
4F	AGR Waste Burning	0.8	0.8	100%	100%	141%	0.4%	0.5%
5A	LUCF Forest fires	6.9	6.5	100%	50%	112%	2.4%	3.7%
6A	WH Landfills	14.8	22.9	50%	50%	71%	5.4%	6.6%
6B	WH Wastewater treatment	2.9	5.1	100%	50%	112%	1.9%	3.0%
6C	WH Waste incineration	0.2	0.2	100%	50%	112%	0.1%	0.1%
6B	WH Wastewater disposal	16.5	27.4	50%	50%	71%	6.4%	8.0%
	Global total	246.8	301.9			23%		18.2%

Source: EDGAR 3.2; uncertainties: Olivier *et al.* (1999) and recent estimates.
U = Uncertainty; AD = Activity data; EF = Emission factor; EM = Emissions.

Table 8. Uncertainty estimate in global total annual methane emissions and in the 1970-1995 trend (IPCC 'Tier 1' trend)

Region	Emissions 1970	Emissions 1995	Annual uncertainty	Ibid. V2.0 default	Emission increase (Tg)	(%)	Uncertainty trend	in Ibid. V2.0 default
OECD'90	70.7	72.2	±12%	±22%	1.5	2%	±9%	±18%
EIT	35.0	44.2	±20%	±19%	9.2	26%	±18%	±17%
LDC	141.2	185.5	±34%	±29%	44.3	31%	±37%	±29%
Sum (combined)	247	302	±21%				±21%	
Global total	247	302	±23%	±27%	55	22%	±18%	±18%

Source: EDGAR 3.2; uncertainties: EDGAR V2.0: Olivier *et al.*(1999) and recent own estimates.

- The annual uncertainty of 23% could be reduced to 16% if the uncertainty of emissions from ruminants and from rice cultivation could be reduced by half; likewise could the trend uncertainty of 22%-points be reduced to 18% if the uncertainty in the amounts of solid waste being landfilled could be reduced by half and activity data and emission factors for wastewater disposed could be reduced by the same fraction.

Please note that the level of accuracy of the uncertainty estimates for emissions is not reflected in the uncertainty figures presented, since they are all calculated from order-of-magnitude uncertainty estimates of underlying data. Also, uncertainty estimates at regional and global levels were not made with formal error propagation calculation of uncertainties estimated for subsources at *national* level, since that was judged not necessary due to the rather aggregated emission factors and aggregated uncertainty estimates for the input data.We conclude that at global and regional levels part of the uncertainty at national level caused by limited precision of national activity data and more importantly emission factors, may be reduced by aggregation to higher spatial levels. This conclusion may, however, be not completely valid for the emission factors used to construct the emission inventories, since these are often based on literature in which sets of emission factors were compiled and reviewed. Therefore we can not exclude that they could contain some bias, although our resulting global or regional emissions are generally in line with other estimates and with atmospheric budgets as presented in Table 6.

5.2 Uncertainties in sectoral emissions at national level

In the process of updating 1990 activity data of countries with more recent statistical datasets, these data are often changed to a lesser or larger degree (Olivier and Peters, 2002). This is caused by the phenomenon that activity data statistics of the most recent years tend to change during a couple of years after the first compilation. This happens in particular in non-OECD countries, however, also in industrialised countries this can be observed, although in these countries the changes are often smaller. We recall that the EDGAR 3 energy data are based on IEA statistics published in 1997 and thus may differ somewhat from most recent IEA datasets; in particular for countries of the former Soviet Union the IEA data have been updated considerably. For methane this is of particular importance for fossil fuel production and transmission. The emission factors we used are often Tier 1 default values recommended by IPCC. It is acknowledged that application to individual countries may result in large errors. In Table 9 e have summarised the 'default' uncertainties estimates by IPCC experts for application of these emission factors at country level provided in IPCC (2000).

To get an impression of the accuracy of our estimates at country level we compared our emission estimates for major sources with official reported national emissions for 1990 by 18 to 33 industrialised countries to the *Climate Convention Secretariat* (Table 10). Assuming that these national emissions estimates are more accurate than our more generic approach – which is not necessarily the case – we can interpret the observed differences as indications of uncertainty in our estimates. The EDGAR 3.2 estimates differ about 12% from the sum of selected country totals, which cover about one third of our global anthropogenic total. Table 9 clearly shows that the largest percentage differences were found in the source categories waste water (6B; 690% ±500%), the oil and gas sector (1B2; 90% ± 90%), and landfills (6A; -20% ±20%). The size of the 2-sigma uncertainty ranges show that the differences for individual countries can be very large in some cases. Examples of large absolute differences are +8 and +2 Tg for coal mining in the USA and Norway, respectively (both differences of 200%) and about +3 Tg for oil and gas in the Russian Federation and in the USA (both differences of 25%).

Beides the uncertainties discussed above we can add the following to the quality of our emission estimates at country level for the major sources (IPCC source category numbers specified between square brackets):

- For emissions from *coal mining* [IPCC category 1B1] our estimate for 1990 (21 Tg) differs substantially from the official estimate for the USA (12 Tg), which may be an indication of the uncertainty level of our Tier 1 approach at country level.
- For the *oil and gas sector* [1B2] the IPCC suggests a very high uncertainty in the emission factors at country level. However, our comparison with official national estimates for two large countries USA and the Russian Federation shows differences of the order of 25 to 35%. Moreover, we want to recall the remark made above on the former USSR.
- For *biofuel combustion* [part of 1A4] the uncertainty in the amounts burned are very high, for 1990 of the order of 100%, except perhaps in Latin America (50%). For the year 1970, we estimate an additional trend uncertainty of about 25%, based on the analysis made for Latin American countries (see Section 3.1.2). According to Andreae and Merlet (2001) the uncertainty in the emission factor for fuelwood is about 30%.

Table 9. IPCC uncertainty estimates at national level for activity data and default IPCC emission factors

IPCC category / Source	IPCC (2000): Good Practice Guidance & Uncertainty Management		IPCC (1997)
	Uncertainty activity data (U_A)	Uncertainty emission factor (U_E)	U_A, U_E,;U_{TOTAL}
1A-Fuel combustion	Power gen., large ind.: 5/10% [1]	100% [50-150%]	7%, ?;?
fossil fuel:	Resid. etc., small ind.: 10/20% [1]	100% [50-150%]	
	Road transport: 5/(10)% [1]	40%	
biofuel:	30/80% [1]	80%	-
1B1-Coal mining	5/10% [1 2]	Tier 1: 100/200/200% ; Tier2: 50-75/100/50%,; for Underground/Surface/ Post-mining, respectively (P.M. recovered fraction)	20%, 55%; 60%
1B2-Oil and gas	5/15% for sales/other activities	Tier 1: ≥ 100%; Tier 3: 25-50%	20%, 55%; 60%
2-Industrial processes [3]	(5%)	(100%)	-
3-Solvents etc. [4]	(10%)	(100%)	-
4A-Enteric fermentation	(5%)	Tier 1: 50%; at minimum 30% Tier 2: 20%	10%, 25%; 25%
4B-Enimal waste	(10%)	Large (50%)	10%, 20%; 20%
4C-Rice cultivation	(5/10%)	basic emission factor: 40%; scaling factors for: - water management: 50% - organic amendments: 100% - soil type: 100% Result: 120%	>60%; relative importance: "¼, ¾; 1"
4E-Savannah burning	?	20%	50%, 50%; 100%
4F-Agricult. waste burning	? (> 50%)	20%	50%, 50%; 100%
5A-Deforestation	?	?	50%, 50%; 100%
6A-Landfills	MSW deposited: >10/>100%	DOC: -50%; +20% DOC_F: -3-%; +0% MCF: 10 to 50% [value 1 to 0.6] F: -0%; +20% k: -40%; +300% (P.M. recovered fraction)	> 60%; relative importance: "1/3, 2/3; 1"
6B-Wastewater - domestic industry:	Domestic wastewater: 30%; Industrial production: 25% Industrial wastewater: 50-100% COD/ton product: 100%	Maximum methane producing capacity B_0: 30% Fractions treated anaerobically: ? (P.M. recovered fraction)	-
6C-Waste incineration	5-10%	(100%)	-
7-International transport	Marine: ? Aviation: 5-100%	100% 100%	-

Figures between brackets are own estimates based on expert judgement. For uncertainties larger than 50% the lower part of the confidence interval is assumed to be 100/(100+[uncertainty (%)]) (in %).

[1] OECD'90/EIT and LDC countries, respectively.

[2] 10% for countries with a mix of regulated and non-regulated mines.

[3] Refers to non-combustion activities, for methane small sources such as production of pig iron, sinter, ethene and styrene.

[4] Refers to product use, for methane small sources such as e.g. tobacco smoking.

Table 10. Comparison of EDGAR 3.2 country estimates for 1990 with official National Inventory Report (NIR) estimates for selected industrialised countries

IPCC category/source	NIR Total (Tg)	EDGAR 3.2 Total (Tg)	E/N total	E/N average individual countries	E/N weighted average	No. (number of countries)
1B1-Solid fuels	12.2	21.3	1.75	1.20 ± 0.49	2.36	18
1B2-Oil and gas	28.0	34.6	1.24	1.87 ± 0.92	1.36	23
4A-Enteric fermentation	24.9	23.1	0.93	0.98 ± 0.06	0.95	32
4B-Enimal waste	5.9	4.2	0.70	1.25 ± 0.46	1.22	32
6A-Landfills	22.7	17.7	0.78	0.78 ± 0.22	0.99	33
6B-Wastewater	1.1	4.8	4.20	7.87 ± 5.24	12.22	25
Total	94.8	105.7	1.12			

Source of NIR data: http://ghg.unfccc.int (visited 17 May 2002).
Note: E/N refers to the ratio of the EDGAR estimate over the official national estimate referred to as 'NIR'. The columns with 'total' refer to the sum of all so-called Annex I countries providing a non-zero 1990 estimate in their NIR; that number of countries is given in the last column 'No.'. The Annex I countries in the *UN Framework Convention on Climate Change* is a group of countries similar to the group of countries belonging to either OECD'90 or EIT.

- For *enteric fermentation* by animals [4A] IPCC experts estimated the uncertainty in the Tier 1 default emission factors of the order of 50%, with a minimum of 30%. Comparison with official country data shows that for most countries our estimates for all livestock together are within 10% of the official national estimates. For emissions from animal waste the differences are higher, up to 25%. With respect to the size of changes over time in emission factors, national reports of five OECD countries to the UNFCCC suggest that the emission factor for enteric fermentation by dairy cattle in the 1990s has increased by about 0.6 (± 0.2)% per year (UNFCCC, 2001).
- If these five are representative for all OECD countries, this would result in emission factors for industrialised countries to be about 12 (± 6)% lower in 1970 then the 1990 value. This is in agreement with the trend in average carcass weight to the power 0.75 for developed countries, which is according to FAO statistics about 17% in the 1970-1990 period; for less developed countries the increase was about 5%. Animal weight to the power 0.75 is a factor included in most terms of the formula to calculate the emission factor for enteric fermentation according to the IPCC Tier 2 methodology. When we would use the limited trend data for the emission factor of dairy and non-dairy cattle as reported for 1990-1998 to the UNFCCC, the global increase of animal emissions in the 1970-1995 period would change from 20% to 25%, which corresponds with emissions in 1970 decreasing by about 2 Tg and in 1995 increasing by almost 1 Tg. However, the uncertainty corresponding to the standard deviation of the average five country trend is about 35% (95% confidence range).
- For *rice cultivation* [4C] our correction of the officially underreported harvested rice area in China of 40% may be towards the upper bound of the uncertainty range. The uncertainty in the national 1990 emission factors is of the order of 100% (Table 8). For the country-specific emission factors from Neue (1997), the uncertainty will be smaller, but due to intrinsic problems in up-scaling still considerable, e.g. 50%.
- The fractions of agricultural waste burned on-site [4F] in developing countries are very uncertain. However, also the decreasing trend in OECD Europe in the 1980s is also fairly uncertain. IPCC experts estimated the uncertainty in the emission factor at 20%.
- For *landfills* [6A], a comparison of total annual amounts of MSW per country generated per capita for 1990 in four studies showed that there are sizeable differences between these figures. These are partly due to different definitions of waste included in this category (e.g. excluding internal waste streams within industry (no MSW), which are re-used in the manufacturing process; other types of re-use or recycling of disposed materials; so-called uncontrolled residential waste handling, e.g. small fires in backyards or illegal dumping), and partly due to the incomplete monitoring of these material streams within society. This causes an average uncertainty for OECD countries of about 17% with extremes of 35% for some countries like Switzerland, the United Kingdom and Greece. As discussed in Section 3.3.1, the values selected for the methane generation constant k and the methane correction factor have a large influence on the calculated emissions. If the k values would have an uncertainty of 100%, which is not

impossible according to IPCC expert judgements listed in Table 8, this factor alone would propagate to an uncertainty in emissions of 25 to 40% in 1995 and 1970, respectively.

- For *wastewater disposal and treatment* [6B], the gross emissions are rather uncertainty for industrial wastewater, due to the large variation in data on the rate of wastewater generation per ton of product as well as in the COD content per product. Moreover data on the fractions treated anaerobically and the fraction of methane recovered in wastewater treatment plants are not readily available. Comparison of our estimates with official national estimates, as mentioned above, shows very large discrepancies for OECD countries. From our gross estimate using a 75% recovery fraction and net emissions officially reported by the countries the conclusion would be that possibly about 98% of the produced methane is captured and used or flared. In summary, the uncertainty in emissions is very large, of the order of 100% or more, but the emissions for WWTPs may also contain a bias to the high side of the uncertainty range, since UNFCC data suggest that the average recovery fraction may be much higher than the 75% we assumed.
- For *large-scale biomass burning* [4E, 5A] including agricultural waste burning [4F], it is generally accepted that there is large uncertainty in the total amounts burned. Although our mix is different, out estimate for total biomass burning in 1990 is comparable with other estimates, e.g. as used by Andreae and Merlet (2001). According to this study their emission factors for forest and savannah fires have and uncertainty of 30% and 40%, respectively.

We conclude that the uncertainty in the resulting dataset at national level may be substantial, caused by the limited accuracy of international activity data used and in particular of emission factors used for calculating emissions on a country level (Olivier *et al.,* 1999, 2001). However, since methods used are comparable with IPCC methodologies and global totals comply with budgets used in atmospheric studies and the data were based on international information sources, this dataset provides a sound basis to serve as a reference database both at national and global level.

5.3 Uncertainty in emissions at grid cell level

The uncertainty at grid cell level of gridded anthropogenic emissions depends firstly on the accuracy of the source estimate at national level and secondly on the proxies used for the within country distribution of the national source total. The first part has already been discussed in the previous section, so here we will limit ourselves to the latter. For a generic discussion of this subject we refer to Olivier *et al.* (1999) and Olivier and Peters (2002). Although it is very difficult to quantify the uncertainty at individual grid cell level, a clear distinction can be made between *point sources* (industrial plants) and so-called *area sources*. Due to its nature as a large group of very many small sources, for example road traffic, the spatial and temporal distributions of area sources often show fairly stochastic (smooth) patterns. This would suggest that gridded maps with related annual total activities per grid cell could result in a rather accurate distribution of national emissions. For methane sources a notable exception could be emissions per type of rice cultivation, where additional uncertainty due to local differences of ecosystem management is directly related to the variability at grid cell level of these such variables as the amount of organic amendments. Also, using population density as proxy for emissions gas distribution networks may introduce additional uncertainty at grid cell level since the networks may not stretch away to all populated areas and because the highest emissions are expected from old pipelines in city areas where in past times gas works gas was distributed. In addition, in large countries where natural gas consumption has been expanded greatly over the last decades, so will the distribution network. This means that in the early days only a spatially limited fraction of the national population was attached to a gas network, much in contrast with present times where population density seems a fair approximation of the national gas distribution network.

On the other hand, the uncertainty at grid cell level can be very high for industrial point sources, since these have a more discrete nature, i.e. individual plants can shut down or open or expand substantially within a short time, thereby changing the emissions pattern substantially. For methane sources this may be important for fossil fuel production, where we have seen a *trend over the last decades* of closing of coal mines and addition of new gas and oil production sites. Also the additional application of methane recovery technologies will generally be focussed on a limited number mines – as will also be the case for CH_4 recovery from landfills. In addition, population maps (total, urban, rural) were used for allocating sources such as landfill and wastewater emissions. For large countries with a high rate of urbanisation it may be relatively important to capture the spatial demographic changes when compiling gridded emission inventories for a longer time period. Inspection of trends for the largest countries shows the following picture (urban percentage in 1970, increase 1970-1995 in percentage points):

- high urbanisation: Australia: 82%, -1%; Canada: 76%, +1%; USA: 74%, +3%;
- medium urbanisation: Russia: 63%, +14; Mexico: 49%, +14%; Brazil: 55%, +23%;
- low urbanisation: India: 20%, +7%; China: 17%, +13%.

This means that using the population and other source-specific maps originally developed for 1990 to distribute the emissions on a grid for other years will generally introduce increasingly large errors at grid cell level. However, it appears fairly probable that in general the migration of fossil fuel production sites and population densities is confined to a few neighbouring 1x1 degree grid cells. Moreover, the importance at global scale is also limited to the extent that this refers only to within-country distributions.

In conclusion, the accuracy of the global emissions of a source at grid cell level is firstly determined by the uncertainty in national emissions within each country border and secondly by the quality of the grid maps used as proxy for the within-country distribution. Using location maps for 1990 for fossil fuel production and human and animal population for years in the past introduces additional uncertainty in the within-country distribution the more remote we go in the past or future, although this added spatial uncertainty may be limited to a few neighbouring grid cells.

6. Conclusions and recommendations

We have compiled an internally consistent inventory for global methane emissions for the period 1970-1995. According to our analysis in this period anthropogenic emissions have increased about 50 Tg from 250 Tg/yr to 300 Tg/yr, whereas the increasing trend is levelling off since the late 1980s. This is in line with observations of the declining growth rate of the atmospheric methane burden as well as with results of semi-inverse modelling. Combined with an estimate of natural sources of about 230 Tg/yr a total of 530 Tg/yr annual emissions in the 1990s is well in line with budgets compiled in recent studies.

Activity data were mostly taken from international statistical data sources and emission factors were selected mostly from international publications to ensure a consistent approach across countries. We acknowledge that the uncertainty in the resulting dataset at national level may be substantial, which is caused by the limited accuracy of international activity data used but in particular of emission factors used for calculating emissions on a country level. Moreover, for some sources there is still substantial uncertainty in emission factors that should be representative for specific national or ecological circumstances. Nevertheless, we believe that this dataset, through its transparancy and clear reference of datasets used in the construction, may serve a valuable purpose both for scientific and policy-oriented applications. Since the methods used are comparable with IPCC methodologies and global totals comply with budgets used in atmospheric studies and the data were based on international information sources, this dataset provides a sound basis for comparability studies. By adjusting specific source categories to other emission levels that are also possible within the constraints of the present or future knowledge base on sources and the atmospheric concentrations of different methane isotopes, users of the EDGAR 3.2 dataset may explore the results, both in space and time, of different 'scenarios' of methane emissions. Likewise, new emission factor datasets proposed for inclusion in emission factor guidelines may be tested for major biases by inclusion in an alternative scenario for specific source categories and check the plausibility of the overall result of the 'fingerprint' of the source strength in space and time, and possibly per 'isotopic type'. Total trend uncertainty in global total anthropogenic methane emissions in 1995 and the 1970-1995 period were estimated using the IPCC Tier 1 uncertainty method for combining uncertainties in activity data and emission factors. From these calculations we conclude that the total global annual uncertainty is about 23% and that the increasing trend of 22% globally has an uncertainty of about ±18% points.

Although we have put much effort in producing a dataset that is as accurate as possible, in the course of time a number of areas were identified in which the dataset could be improved:

- inclusion of emission factor trends for livestock, in particular for dairy cattle;
- improvement of the geographic basis for the emission factor trends for coal mining and rice production;
- refinement of fractions of agricultural waste burned on the fields in developing countries and in Europe;
- incorporation in the dataset of the interannual variation in tropical forest and savannah fires, especially for El Nino years;
- making available process models for calculating the emissions of wetlands as a function of local weather data;
- improved estimation of uncertainties by collective expert judgement.

Further improvements could be made by looking into more country-specific figures for key anthropogenic sources like:

- data required for calculating emissions from livestock using the IPCC Tier 2 approach;
- parameters needed for estimating landfill emissions;

- information required for calculation of net wastewater emissions, e.g. recovery fractions and fractions treated anaerobically in WWTP;
- to aid inverse modellers in 'fingerprinting' the main source categories, besides a fair description of the spatial distribution and interannual variation, also the seasonality of the sources may be improved. Available data suggests that anthropogenic sources other than rice production and large-scale biomass burning may show larger seasonal variation than often is assumed by modellers.

The datasets of regional trend data, per country estimates for recent years as well as gridded emissions are made publicly available at the EDGAR website (http://www.rivm.nl/env/int/coredata/edgar). This includes supplementary datasets such as the country to grid relation table and the climate zone fractions per country as calculated for this study.

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APPENDIX

Table A.1. Methane emissions per source category and region in 1970 and 1980 (source: EDGAR 3.2)

IPCC code/source category	Total	OECD '90	EIT	LDC	Canada	USA	OECD Europe	Oceania	Japan	Eastern Europe	Former USSR	Latin America	Africa	Middle East	South Asia	East Asia	SE Asia
Year: 1970																	
1B1-Coal mining	32	18	9	5	0.1	9.4	6.7	0.4	1.3	3.5	5.7	0.2	0.6	0.1	0.5	3.4	0.0
1B2-Gas production/transmission	20	11	8	1	0.6	9.6	0.4	0.0	0.0	1.2	6.6	0.3	0.0	0.8	0.1	0.1	0.0
1A/1B2-Other fossil fuel use	11	4	3	5	0.2	2.0	1.2	0.1	0.1	0.5	2.2	1.3	1.3	1.4	0.1	0.8	0.2
1A/B-Biofuel use	9	0	1	8	0.0	0.1	0.2	0.0	0.1	0.1	0.5	0.6	1.9	0.1	2.4	2.1	1.1
2-Industry, non-combustion	1	0	0	0	0.0	0.1	0.2	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
4A/B-Animals	74	21	11	42	1.0	7.8	8.2	4.1	0.2	2.9	8.1	12.7	7.3	1.7	12.0	5.4	2.4
4C-Rice cultivation	51	1	0	50	0.0	0.3	0.2	0.0	0.1	0.0	0.2	0.9	0.7	0.2	16.8	22.1	9.7
4F-Agricultural waste burning	1	0	0	0	0.0	0.0	0.3	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1
4E-Savannah burning	6	0	0	6	0.0	0.0	0.0	0.4	0.0	0.0	0.0	1.9	3.8	0.0	0.0	0.1	0.1
5A-Tropical forest fires	7	0	0	7	0.0	0.2	0.0	0.1	0.0	0.0	0.0	3.5	1.2	0.0	0.2	0.2	1.5
5A-Temperate forest fires	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6A-Landfills	15	12	1	2	0.8	6.4	3.8	0.2	0.6	0.3	1.0	1.0	0.2	0.1	0.2	0.2	0.1
6B-Waste water handling	20	3	2	15	0.2	1.1	0.9	0.2	0.3	0.6	1.3	2.3	1.7	0.5	4.3	4.5	1.8
Total	247	71	35	141	3.0	37.2	22.0	5.6	3.0	9.2	25.8	24.8	18.7	5.1	36.7	39.0	17.0
Year: 1980																	
1B1-Coal mining	33	16	10	8	0.1	9.6	5.0	0.5	0.5	4.2	5.8	0.3	0.9	0.1	0.8	5.4	0.1
1B2-Gas production/transmission	29	11	15	3	0.9	9.1	1.1	0.1	0.2	2.0	12.9	0.6	0.2	1.3	0.1	0.2	0.6
1A/1B2-Other fossil fuel use	14	3	4	7	0.3	1.8	0.9	0.2	0.1	0.6	3.3	1.4	1.5	1.8	0.1	1.5	0.5
1A/B-Biofuel use	11	0	1	10	0.0	0.1	0.1	0.0	0.0	0.1	0.4	0.6	2.5	0.1	3.0	2.5	1.4
2-Industry, non-combustion	1	0	0	0	0.0	0.1	0.2	0.0	0.1	0.1	0.2	0.0	0.0	0.0	0.0	0.1	0.0
4A/B-Animals	83	22	13	49	1.0	7.7	8.6	4.0	0.3	3.4	9.5	16.4	8.4	1.9	13.4	6.0	2.3
4C-Rice cultivation	47	1	0	46	0.0	0.5	0.1	0.0	0.1	0.0	0.3	0.9	0.7	0.2	14.5	20.1	9.1
4F-Agricultural waste burning	1	0	0	0	0.0	0.0	0.3	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.1
4E-Savannah burning	6	0	0	6	0.0	0.0	0.0	0.4	0.0	0.0	0.0	1.8	3.8	0.0	0.0	0.1	0.1
5A-Tropical forest fires	7	0	0	7	0.0	0.2	0.0	0.1	0.0	0.0	0.0	3.5	1.2	0.0	0.2	0.2	1.5
5A-Temperate forest fires	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6A-Landfills	20	15	2	3	1.0	8.6	4.4	0.3	0.9	0.4	1.4	1.5	0.2	0.2	0.3	0.3	0.1
6B-Waste water handling	24	3	2	19	0.2	1.3	0.9	0.2	0.4	0.6	1.4	3.0	2.3	0.7	5.4	5.5	2.3
Total	276	73	47	156	3.5	39.0	21.7	5.8	2.6	11.5	35.5	30.1	21.7	6.4	37.9	42.0	18.1

Table A.2. Methane emissions per source category and region in 1990 and 1995 (source: EDGAR 3.2)

IPCC code/source category	Total	OECD '90	EIT	LDC	Canada	USA	OECD Europe	Oceania	Japan	Eastern Europe	Former USSR	Latin America	Africa	Middle East	South Asia	East Asia	SE Asia
Year: 1990																	
1B1-Coal mining	36	16	8	12	0.2	11.9	3.2	0.7	0.2	3.1	5.0	0.3	1.2	0.1	0.9	9.0	0.2
1B2-Gas production/transmission	45	11	26	7	1.1	8.4	1.3	0.2	0.4	2.0	23.9	0.9	0.5	3.2	0.4	0.2	2.1
1A/1B2-Other fossil fuel use	14	3	4	7	0.3	1.7	0.8	0.2	0.1	0.5	3.2	1.6	1.5	1.4	0.2	2.2	0.5
1A/B-Biofuel use	13	0	0	12	0.0	0.3	0.1	0.0	0.0	0.1	0.4	0.6	3.2	0.1	3.6	2.8	1.7
2-Industry, non-combustion	1	0	0	0	0.0	0.1	0.2	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.1	0.0
4A/B-Animals	89	20	13	56	0.9	6.8	8.2	4.0	0.3	3.1	9.7	18.4	9.4	1.9	15.2	7.8	2.9
4C-Rice cultivation	39	1	0	38	0.0	0.3	0.1	0.0	0.1	0.0	0.2	0.7	0.7	0.2	12.4	15.8	8.3
4F-Agricultural waste burning	1	0	0	0	0.0	0.1	0.2	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.1
4E-Savannah burning	6	0	0	6	0.0	0.0	0.0	0.4	0.0	0.0	0.0	1.7	3.8	0.0	0.0	0.0	0.1
5A-Tropical forest fires	5	0	0	5	0.0	0.0	0.0	0.1	0.0	0.0	0.0	2.5	1.0	0.0	0.1	0.1	1.4
5A-Temperate forest fires	1	1	0	0	0.2	0.5	0.1	0.1	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
6A-Landfills	22	16	3	4	0.9	9.4	4.1	0.3	1.1	0.6	1.9	2.2	0.4	0.3	0.4	0.5	0.2
6B-Waste water handling	30	4	2	24	0.2	1.6	1.0	0.3	0.4	0.6	1.6	3.8	3.2	0.9	6.9	6.5	2.9
Total	302	73	57	172	4.0	40.8	19.3	6.5	2.7	10.0	46.6	32.9	25.0	8.5	40.2	45.1	20.2
Year: 1995																	
1B1-Coal mining	33	14	6	14	0.2	10.4	2.1	0.8	0.2	2.8	2.8	0.3	1.3	0.1	1.2	11.1	0.3
1B2-Gas production/transmission	44	13	21	10	1.5	9.6	1.6	0.3	0.5	1.6	19.4	1.1	0.6	4.4	0.5	0.3	3.1
1A/1B2-Other fossil fuel use	13	3	2	8	0.3	1.5	0.7	0.2	0.1	0.3	1.9	1.9	1.6	1.6	0.2	2.1	0.6
1A/B-Biofuel use	14	1	0	13	0.0	0.3	0.1	0.0	0.0	0.1	0.3	0.5	3.6	0.2	4.0	2.9	1.8
2-Industry, non-combustion	1	0	0	0	0.0	0.1	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.2	0.0
4A/B-Animals	89	20	10	59	1.0	7.1	7.5	3.8	0.3	2.1	7.5	19.1	9.8	1.9	15.9	9.3	3.3
4C-Rice cultivation	39	1	0	38	0.0	0.3	0.1	0.0	0.1	0.0	0.2	0.9	0.8	0.2	12.3	14.6	9.2
4F-Agricultural waste burning	1	0	0	1	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.1
4E-Savannah burning	6	0	0	6	0.0	0.0	0.0	0.4	0.0	0.0	0.0	1.7	3.8	0.0	0.0	0.0	0.1
5A-Tropical forest fires	5	0	0	4	0.0	0.0	0.0	0.1	0.0	0.0	0.0	2.0	1.0	0.0	0.1	0.0	1.3
5A-Temperate forest fires	2	2	0	0	1.5	0.2	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
6A-Landfills	23	15	3	5	1.0	8.4	4.0	0.3	1.2	0.7	2.2	2.9	0.5	0.4	0.5	0.6	0.2
6B-Waste water handling	33	4	2	27	0.3	1.9	1.0	0.3	0.4	0.5	1.5	4.3	3.7	1.1	7.6	7.0	3.2
Total	302	72	44	186	5.8	39.8	17.4	6.3	2.9	8.2	36.0	35.1	26.7	9.9	42.3	48.2	23.3

5. Review of Inventories of Natural Emission Sources

5.1. Introduction

When evaluating the effects of anthropogenic emissions of most compounds at any spatial level, the natural sources also need to be considered, since these may contribute substantially to total global or local emissions. This is illustrated in the paper presented in the next section, which serves as a brief review of gridded inventories available either as GEIA inventory or otherwise published and available for use.

Natural emissions are defined here as non-anthropogenic emissions stemming from processes either in the soil or vegetation, or in the oceans and other surface waters, or in the earth's crust (e.g. volcanoes or gas/oil seepage) and even in the atmosphere (e.g. lightning). Notable is that in the emission inventory literature, the distinction between anthropogenic and natural sources is neither always straightforward nor consistent. For policy purposes a specific definition of anthropogenic sources has often been made, the complement then being natural sources *by definition*. Examples of 'borderline' activities are:

- wild animals: even when considered not to be managed, animals living in a nature reserve could be considered to be 'managed', since the reserve as a whole is managed by humans;
- vegetation fires in temperate regions: a large fraction of so-called wildfires are, in fact, assumed to be caused by humans. Prescribed fires, but other forms of fire suppression activities too, form a kind of forest management;
- changes in biogenic emissions from soils due to human-induced changes in the groundwater level;
- additional or sooner deposition caused by anthropogenic air pollution, giving rise to subsequent re-emissions of NH_3 and N_2O, for example.

Natural emission sources, in particular the *biogenic* sources among them, are dependent on the conditions in the local environment. Thus, large datasets on such parameters as temperature, precipitation, soil characteristics, oceanic parameters and aerial concentration of the compound need to be taken into account. The natural emission inventories are the result of modelling the underlying processes using these global datasets at a specific spatial and temporal resolution (grid cells and time period). As a consequence, many of the calculated global total source strengths have substantial uncertainty, which is mainly due to the limited knowledge about specific local conditions as well as the variability of the determining parameters within each grid box and the time period considered. In the subsequent section, the uncertainty range surrounding the global total for most species is specified.

5.2 Review of existing inventories of natural sources

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Introduction

The *Global Emissions Inventory Activity* (GEIA) aims at providing global gridded emissions inventories to science and policy communities for all trace gases, in particular those that are relevant for global atmospheric chemistry. These emissions may stem from anthropogenic or natural sources. Natural sources may relate to processes in the soil (e.g., bacteria), in vegetation (plants), in the oceans (emissions from dissolved amounts or produced by algae [but oceans may also act as a *sink* by absorption and dissolution in the water]), in the Earth's crust (volcanoes or gas/oil seepage), or in the atmosphere (lightning). These emissions often depend strongly on climate, soil or water characteristics and thereby show a strong temporal variation, in seasonality, diurnal cycle or both. Thus, natural sources often have a distinctly other character than have anthropogenic sources, which are comparably constant with respect to seasonality. In addition, the source strength as well as the spatial distribution of natural sources may differ substantially from year to another. An extreme example are volcanic emissions. Besides natural sources, natural sinks may occur locally, e.g. in some ocean areas where compounds are absorbed from the atmosphere.

Even if one is primarily interested in the effect of man-made emissions, the background of natural emissions (or sinks) of the same compounds and of related species must also be considered. For example, large datasets concerning temperature, precipitation, soil characteristics and oceanic parameters must be taken into account. Many of the natural emissions inventories are thus the result of modelling of the underlying processes using these global datasets. The resulting emission inventories either relate to a multi-year average showing the characteristic spatial and seasonal distribution of the natural emission sources or present episodic inventories for specified years, based on geo and climate data for these specific years.

In this paper we will review the GEIA emissions inventories of natural sources, but also discuss some others published in the literature and compare their global source strengths with anthropogenic sources.

GEIA inventories

Species presently covered by GEIA are related to acidification, ozone depletion, tropospheric ozone formation, climate change, aerosol formation and pollutants such as heavy metals and persistent organic pollutants (POPs), that are poisoning people and ecosystems. The extent to which N-, S- Cl- and C-containing compounds and other species are emitted by natural sources differs from compound to compound. For example, in Figure 1 total global emissions from natural and anthropogenic sources of NO_x, NH_3 and N_2O are compared. It clearly shows that the share of man-made emissions in the total source strength can differ considerably but also that uncertainties can be quite large.

Emission inventories are available for the following species:

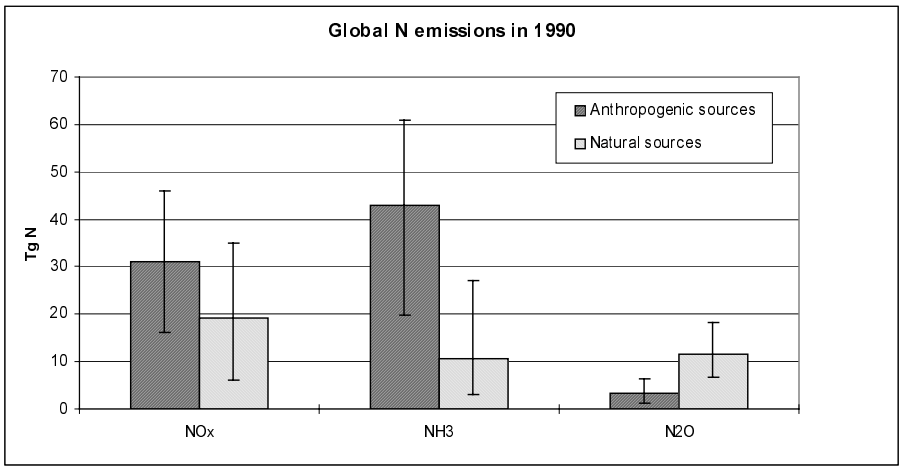

Figure 1. Contribution and uncertainty of global anthropogenic and natural N emissions in 1990 [from Olivier *et al.* (1998)].

Table 1. Natural emissions of nitrogen and sulfur compounds.

Source/Compound	Emission (Tg N or S/yr)	Reference
NO_x emissions:		
- soils (including canopy sink)	5.5 (4-12)	Yienger and Levy [1995]
	13 (10-21)	Davidson and Kingerlee [1997]
- lightning	12.2 (5-25)	Price *et al.* [1997a,b]
	5 (2-10)	Pickering *et al.* [1997]
NH_3 emissions:		
- naturals soils	2.4 (0-10)	Bouwman et al. [1997]
- oceans	8.2 (3-16)	Bouwman et al. [1997]
- wild animals	0.1 (0-1)	Bouwman et al. [1997]
N_2O emissions:		
- natural soils	7.5 (3.7-11.3)	Bouwman et al. [1995]
- oceans	3.6 (2.8-5.7)	Nevisson *et al.* [1995]
- freshwater and coastal ecosystems	1.9 (1-9)	Seitzinger and Kroeze [1998]
S emissions:		
- volcanoes: SO_2	6.5 (25 yr average)	Andres and Kasgnoc [1998]
Other S species	3.7 (25 yr average)	Andres and Kasgnoc [1998]
- oceans: DMS	p.m.	[Various models]

- acidification: NO_x from soils and lightning; NH_3 from natural soils, oceans and wild animals;
- aerosol formation: SO_2 from volcanoes; DMS from oceans;
- climate change: CH_4 from wetlands, termites, oceans/hydrates; N_2O from natural soils and oceans;
- tropospheric ozone: CO from vegetation and oceans; NMVOC from vegetation;
- major reactive chlorine compounds: CH_3Cl, $CHCl_3$, CH_2Cl_2, C_2HCl_3, and C_2Cl_4 from oceans; CH_3Cl and $CHCl_3$ from land-based sources; HCl and $ClNO_2$ from sea salt dechlorination.

For the following sources inventories are in progress:

- radionuclides;
- emissions from natural biomass burning (wildfires in temperate regions) (for various species).

Natural CH_4 inventories do not reside at the GEIA website, but are available at http://www.giss.nasa.gov/data/ch4fung/. Inventories for DMS from oceans are published in the literature, but not yet available at the GEIA site. Natural CO emissions from vegetation and oceans are discussed in the literature and used by many atmospheric modellers, but to date no comprehensive emission inventory at 1x1 degree has been compiled. Within the EU-funded project 'POET' which studies the **P**recursors CO, NO_x, CH_4 and NMVOC of **O**zone and their **E**ffect on the **T**roposphere [Granier *et al.*, 1999], the gridded inventory for CO from vegetation will be based on the GEIA inventory for NMVOC from vegetation by Yienger and Levy [1995] and the small ocean source of 13 Tg CO will be based on Bates *et al.* [1995]. Resulting gridded emission inventories will be made available for the IGAC modelling community at large.

N- and S-inventories

For the natural sources of the nitrogen compounds NO_x, N_2O, NH_3, mainly soils under natural vegetation and oceans the reader is referred to Bouwman *et al.* [1995; 1997] for detailed descriptions of inventories of N_2O and NH_3, to Yienger and Levy [1995] for NO_x from soils and vegetation and to and Price *et al.* [1997a,b] for NO_x from lightning. Davidson and Kingerlee [1997] present an alternative estimate of global NO_x emissions from soils, but they do not provide gridded emissions. In Nevisson *et al.* [1995] a more detailed description is provided of N_2O emissions (and regional sinks) from oceans. Furthermore, Seitzinger and Kroeze [1998] have developed a global inventory of N_2O freshwater and coastal marine ecosystems, originating from N inputs from - mainly - anthropogenic sources (so-called indirect N_2O emissions, mainly from agriculture). The vertical profile of lightning emissions may be taken from Pickering *et al.* [1998], which also provide an uncertainty range of 2-10 Tg N/yr, whereas Price *et al.* [1997b] conclude from a constraint analysis that the range would be 5-25 Tg N/yr. As is the case for soils, also for lightning alter-

native datasets exist in the literature, but these are not always available on a 1x1 degree grid. As illustrated in Figure 1, total natural emissions of nitrogen gases have a share of 40%, 20% and 80% in the global total emission of NO_x, NH_3 and N_2O, respectively. On the sulfur emissions from volcanoes we refer to Andres [2000].

CO, CH_4 and NMVOC inventories

Interestingly, for CO at present no inventories on 1x1 degree are reported for the natural sources vegetation and oceans. Müller [1992] presented an emission inventory on 10x10 degrees for oceanic emissions of 162 Tg/yr based on Erickson, but has revised his estimate to 20 Tg/yr, and Bates *et al.* [1995] estimate the ocean source at 13 Tg/yr. However, various estimates are reported in the literature and in the 1997 GIM/IGAC model intercomparison of 3D tropospheric CO distributions a range of source strengths were used [Kanakidou *et al.,* 1999].

For vegetation/soil the average was 160 Tg/yr within a range of 100-280 Tg/yr; for oceans these values were 50 (13-162) Tg/yr. Table 2 provides an overview of the various estimates found in the literature, including the 'best estimate' provided by Khalil [2000] in the introduction of the Special Issue on CO of *Chemosphere: Global Change Science*, No. 1 of 1999. For comparison, we note that the second IPCC Assessment Report of 1996 estimated vegetation and ocean emissions to be in the range of 60-160 Tg/yr and 20-200 Tg/yr, respectively. Within the framework of EDGAR 3.0, an estimate is made of CO emissions from vegetation fires in temperate regions, which is 35 Tg in 1995 [Olivier *et al.,* 2001]. In addition, the global CO budget includes a soil sink, of which the total strength and spatial distribution is generally calculated from the surface CO concentrations and the assumed deposition velocity.

Matthews and Fung [1987] presented an gridded inventory of CH_4 from natural wetlands based on an extensive analysis and arrived at a source strength of 110 Tg/yr. Matthews [2000] reviews the literature up to 1997 and concludes that estimates of wetland emissions are converging to a level around 100 Tg/yr, however with an uncertainty still of about 50%.

Table 2. Natural emissions of CO, CH_4 and NMVOC.

Source/compound	Emissions (Tg N/yr)	Reference
CO emissions:		
- vegetation	75 (50-100)	Seiler and Crutzen [1990]
	90 (20-200)	Khalil and Rasmussen [1990]
	160 (100-280)	Kanakidou *et al.* [1999] (model intercompari-
	230 (100-400)	Khalil [1999]
- oceans	100 (10-190)	Seiler and Crutzen [1990]
	13 (6-30)	Bates *et al.* [1995]
	50 (20-80)	Khalil and Rasmussen [1990]
	50 (13-162)	Kanakidou *et al.* [1999] (model intercompari-
	10 (0-30)	Khalil [1999]
- temperate vegetation fires	35 (25-75)	Olivier *et al.* [2001]
CH_4 emissions:		
- wetlands	110 (50-170)	Matthews and Fung [1987], Matthews [2000]
- termites	20 (?-?)	Fung *et al.* [1991]
	20 (18-22)	Sanderson [1995]
- hydrate/clathrates	10 (?-?)	Fung et al. [1991]
- gas seepage	? (8-65)	Hovland *et al.* [1993]
	55 (50-60)	Lambert and Schmidt [1993]
- open ocean	3.5 (3-4)	Lambert and Schmidt [1993]
- oil seepage	p.m.	
NMVOC emissions:		
- vegetation: isoprene	503 (200-800)	Guenter et al. [1995]
monoterpene	127 (50-500)	Guenter et al. [1995]
- oceans: isoprene	5 (?-?)	Guenter et al. [1995]
- gas seepage	p.m.	Hovland *et al.* [1993]
- marine oil seepage	0.6 (0.2-6)	Wilson *et al.* [1774] (maximum if all is oil discharged is emitted into the air)

Recently, Darras *et al.* [1999] have reported on a IGBP-DIS Wetland Data Initiative to determine the global extent of wetlands. In this paper the Matthews and Fung dataset was compared to three other wetland datasets (ISLSCP, DISCover and Ramsar). Fung *et al.* [1991] and Gornitz and Fung [1994] provide gridded inventories for CH_4 from termites and hydrate/clathrate in the Soviet Arctic and between 76° and 85° N of 20 and 10 Tg CH_4/yr, respectively. These inventories, however, are highly uncertain. An alternative inventory of termites emissions, with the same global source strength of 20 Tg/yr is presented in Sanderson [1996]. All of these inventories, except the termites of Sanderson, are available at http://www.giss.nasa.gov/data/ch4fung/.
Finally, within the framework of the POET project [Granier, 1999], an CH_4 and NMVOC inventory for emissions from oil and gas seepage from continental shelfs and from land will be developed. This will be based on Hovland *et al.* [1993] for CH_4 from gas seepage through the seabed, presenting a global total estimate of 8-65 Tg/yr of CH_4, of which a fraction will pass the water column and into the atmosphere. This paper builds on a study by Wilson *et al.* [1994], that provides an estimate of natural marine oil seepage of 0.2-6 Tg/yr oil discharged into the water with a best estimate of 0.6 Tg/yr. A part of the oil will dissolve and emit into the air. Lambert and Schmidt [1993] argue that the oceanic source of methane is likely to be 50-60 Tg/yr, of which 3.5 (3-4) Tg/yr is emitted from open ocean. Clark *et al.* [2000] measured that gas bubbles at the ocean surface contain about 60% CH_4 and about 10% NMVOC. The seepage inventories are on the continental shelf in addition of the hydrate/clathrate source estimated by Fung *et al.* [1991].

The major natural source of NMVOC is vegetation, although the global source strength is rather uncertain [Guenter *et al.*, 1995]. The main compound groups emitted by plants and trees are isoprenes and monoterpenes. In addition, there area few small oceanic sources (see Table 2). The natural NMVOC inventory is discussed in more detail in Guenther (2000).

Reactive chlorine emission inventories (RCEI)

Recently a comprehensive set of gridded inventories of reactive chlorine compounds has been published in a series of eight consecutive papers in *Journal of Geophysical Research - Atmospheres,* 104 (D7), 8331 to 8440, 15 April 1999. These include estimates of natural sources, of which the global source strength is summarised in Table 3. Oceans appear to account for about 12% of the global annual emissions of methyl chloride, much lower than often has been assumed. For chloroform emissions from both oceans and land appear to be the major sources.

Table 3. Natural emissions of reactive chlorine species.

Source/compound	Emission (Gg Cl/yr)	Reference
Oceanic emissions:		Khalil *et al.* [1999]
CH_3Cl	460	
$CHCl_3$	320	
CH_2Cl_2	160	
C_2HCl_3,	20	
C_2Cl_4	20	
Land-based emissions:		Khalil *et al.* [1999]
CH_3Cl	100	
$CHCl_3$	200	
Sea salt dechlorination:		Erickson III *et al.* [1999]
HCl	7600	
$ClNO_2$	60	

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6. Quality Assessment of Global Emission Inventories

6.1 Introduction

Emission inventories compiled using a direct estimation approach may be based on different data sources. The selection of the datasets for key elements, activity data, emission factors and - in the case of spatially distributed emissions - grid maps for allocating emissions on a specific grid, may be based on different criteria. Often there are multiple datasets of international statistics available that can be used for activity data, e.g. energy, industrial production of basic commodities, population and gross domestic product (GDP). For emission factors there are many data sources. Certainly at national level, but also at regional/global level, multiple guidelines for default emission factors do exist. Examples are the European ECE/CORINAIR handbook for emission factors, the North American AP-42 emission factor handbook and the IPCC guidelines for national greenhouse gas inventories. For emission factors in particular, one has to be careful to identify the emission factors that have indeed been independently established. Quite often references for emission factors do not refer back to the primary reference, which means that it may go unobserved that a factor may have an origin identical to another factor: both seem to have the same value by accident and to be independently derived. Moreover, there is also a possibility that different grid maps could be used for spatially allocating particular sources, such as different population density maps or maps for one topic compiled for different years.

Given this portfolio of choices that the inventory compiler can and has to make, key questions arising are:

- What difference does the selection of an alternative dataset make in the final emission inventory?
- Or, alternatively, how do the results of two inventories compare to each other?
- Can one inventory be regarded as a better estimate than the other?
- What means are available for validation and verification of emission inventories?

In this chapter the results of comparing different estimates for national CO_2 emissions from fossil fuel combustion and cement production are first presented, where the main differences originate in differences in the international statistical datasets of the activity data. These differences may indicate the (relative) accuracy of specific parts of the datasets (countries, fuel types). Subsequently, an overview is presented of the various options for validation (checking the internal consistency and correctness) and verification (comparing with independent data) that can be performed at national and at international level. Interestingly, when a group of countries compiles their own national emission inventories independently, intercomparison of emission factors used by different countries is an additional option, which can very efficiently show the spread in (aggregated) emission factors or reveal outliers in emission factors. Outlier values do not necessarily mean that those emission factors are in error, but merely that country-specific circumstances could be important for that particular source. The spread could also be interpreted as indicator of the uncertainty in emission factors. However, also in reverse, the absence of a large spread in emission factors used does not necessarily mean that the results are very accurate; it could well be that countries have applied identical emission factors from the same data source.

6.2 Comparison of two independently developed global inventories

This paper has been published as:
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CO_2 from fossil fuel burning: a comparison of ORNL and EDGAR estimates of national emissions

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Abstract

There is increasing interest and importance in estimating national emissions of greenhouse gases. We enquire whether two (partially) independent estimates of emissions of CO_2 from fossil-fuel combustion provide insight into the quality or uncertainty of emissions estimates. Using two published data sets that estimate CO_2 emissions for all countries, we show that the two ostensibly similar efforts to estimate emissions using ostensibly similar energy statistics have produced results that differ significantly for many countries. There is no obvious systematic bias between the two data sets and the two produce very similar estimates for the total of global emissions. Absolute differences between the two estimates are largest for a few countries with very large total emissions, but the largest relative differences occur in countries with small total emissions and weaker national systems of energy statistics. The magnitude of the differences reported has important implications for monitoring and verification of national emissions and potential national commitments.

With increasing concern about greenhouse gas emissions there is increasing commitment for countries or other entities to estimate national emissions. With this comes an increasing number of estimates that purport to represent the emissions from a given country or area. Ratification of the Kyoto Protocol (UNFCCC, 1997) would place binding commitments on some countries to hold greenhouse gas emissions to quantified limits and would raise additional issues of monitoring and verification with respect to these limits.

Given multiple estimates for emissions from the same area, can we either determine which estimate best represents reality or use the multiple estimates to learn something about the quality or uncertainty of the estimates reported? For CO_2 emissions from fossil-fuel combustion there are now two studies that report emissions for all countries in 1990 and are available electronically in compatible format, and thus provide us an opportunity to do a systematic comparison. These two studies are not fully independent and yet they have sufficient independence that we believe the comparison provides useful insight into the uncertainty of the emissions estimates. The comparison of estimates also helps us to understand where resources should best be devoted if we wish to reduce the uncertainty of emissions estimates. The two estimates to be compared come from the Carbon Dioxide Information and Analysis Center (CDIAC) at the Oak Ridge National Laboratory in the US, and the National Institute of Public Health and the Environment and The Netherlands Organization for Applied Scientific Research (RIVM and TNO) in the Netherlands.

Estimates of CO_2 emissions are based on measures of energy use and on coefficients to represent emissions per unit of energy use. Emissions coefficients depend on fuel chemistry and combustion efficiency and thus vary with fuel type and often with the source of the fuel and with time. The two major sources of international statistics on energy production, trade, and use are the United Nations and the International Energy Agency, although other groups such as British Petroleum Company and the World Energy Council also maintain extensive and useful compilations. This analysis calls only on the UN and IEA data sets. These are not independent data sets as they rely on some of the same sources for national energy data, and yet they depend ultimately on the resources and insights of the respective statistical offices. Currently the IEA circu-

lates an annual questionnaire to the energy statistics offices of countries that are members of the Organization for Economic Cooperation and Development (OECD) while the UN circulates a similar (but notably different) questionnaire to countries that are not OECD members. The two organizations then share the responses to their questionnaires with each other. Since many nations do not respond, or do not respond completely, to the questionnaires, the UN and IEA then rely on other national and corporate resources to supplement and amend the submitted data. The two data sets differ somewhat in approach, in categories reported, in emphasis. The UN data set focuses on production and trade of energy resources while the IEA data set places greater emphasis on energy conversion and consumption. In the UN energy data set "apparent consumption" is estimated as the sum of production and imports less exports and increases in storage. Our preliminary comparisons of recent-year data reveal that the two data sets often end up with the identical number for an apparently identical category, but that this is also often not true. Earlier comparisons, e.g. that by Von Hippel *et al.* (1993), show clearly that CO_2 emissions estimates based on these two energy data sets produce very similar global totals but very large differences for some countries.

Emissions coefficients for the CDIAC (identified in the figures below as "ORNL", Oak Ridge National Laboratory) and RIVM/TNO (Identified in the figures below as "EDGAR", Emission Database for Global Atmospheric Research) estimates are very similar although not identical. The CDIAC analyses have been pursued for over 20 years (Marland *et al.*, 1994) while EDGAR is a more recent undertaking and has, in many cases, adopted CDIAC emissions coefficients for comparable fuel categories (Olivier et al., 1997). The ORNL coefficients cover only primary fuels, however, and EDGAR has emissions coefficients for both primary and secondary fuels, as explained below. Both ORNL and EDGAR have proceeded beyond the country data to estimate CO_2 emissions for 1×1 degree latitude/longitude grid cells over the earth and this makes an additional interesting comparison, although it is not pursued in this paper.

To begin to try to understand the differences between various estimates of CO_2 emissions and their implications for data uncertainty and for improving estimates, we have systematically compared the ORNL and EDGAR data sets. Both estimates are for the year 1990. There are important differences for which we have tried to compensate in the comparison. ORNL has estimated emissions from consumption of the primary fuel types; solid (coal, lignite, peat), liquid (crude oil and natural gas liquids), and gas (natural gas). Emissions from flaring of natural gas and from calcining limestone to make cement are included. The EDGAR data set has emissions according to end use sector and final consumption of both primary and secondary fuels. One consequence is that refinery gas, for example, will show under the primary liquid fuel in the ORNL data but as a secondary gaseous fuel in the EDGAR data. The ORNL national data sets do not include oxidation of hydrocarbons used for non-fuel purposes (such as lubricants and asphalts) so for the comparison these emissions have been subtracted from the EDGAR emissions estimates. Both data sets exclude emissions from marine bunker fuels as the current guidelines for estimating national greenhouse gas emissions (IPCC/OECD, 1995) suggest that bunker fuels not be included in national totals. The ORNL data also exclude some international aircraft fuels, as permitted in the IPCC/OECD Guidelines. In the gridded EDGAR data set it is not possible to distinguish between domestic and international aircraft fuels so all aircraft fuel consumption is subtracted out. ORNL has taken data for cement production from the US Bureau of Mines (Solomon, 1994) while EDGAR uses cement data from the United Nations (UN, 1995). Although EDGAR places primary reliance on energy data from the IEA, it does use UN data for some countries not included in IEA tabulations. The result of making the adjustments noted above is that we compare not the total national CO_2 estimates from the two data sets but rather slightly modified totals that come close to including the exact same components. To give an idea of how much carbon is omitted by the selection process described, the ORNL estimate of global total CO_2 emissions from fossil fuel combustion and cement manufacture in 1990 is 6109×10^6 tons of carbon, and the sum of the country estimates used in this comparison is 5749×10^6 tons of carbon.

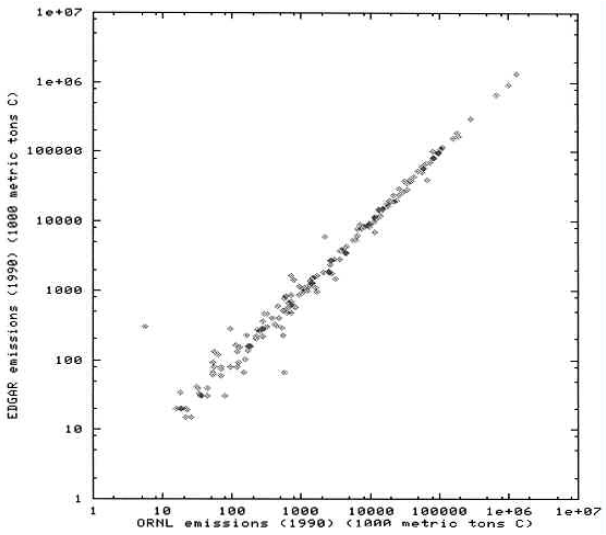

Fig. 1. Correlation of countries' total emissions as calculated by EDGAR and ORNL.

Given thus two closely comparable estimates of national emissions of CO2, how do they compare and what can we learn from the differences? Fig. 1 is a graph of EDGAR emissions estimates for all countries

plotted against the comparable values from ORNL. Because of the large range of values we have plotted the values on a logarithmic scale. Although having a logarithmic plot (Fig. 1) captures the large range of values, it gives a slightly distorted visual impression of the linear best fit. The linear regression produces a best-fit relationship of $y = 316 + 0.97x$, where y is the EDGAR value and x the ORNL value. With an R^2 of 0.99, it is apparent that the two estimates are highly correlated and it is visually apparent that, at this scale, the plot nearly follows the 1:1 relationship expected. There are a few values that fall well off of the 1:1 line, mostly at the lower end of the emissions scale.

At the high end, the log scale of Fig. 1 conceals the absolute magnitude of the differences. In Table 1 we show the absolute magnitude of the difference for the ten largest differences. Note that the difference between the ORNL and EDGAR estimates for the USSR is only 8.1% and yet this amounts to 79 million tons of carbon, a number that exceeds the total emissions from all but the 14 largest emitting countries. The difference between the two estimates for US emissions is 12 million tons of carbon, only 0.9% of US emissions but larger than the total emissions from 147 of the 195 countries for which some data are available. If we sum the differences between the two estimates without regard to sign, the difference in the top 5 countries is larger than the total for the remaining 190 countries. This suggests that if our aim is to improve global estimates of CO_2 emissions we need to focus attention on fuel statistics in only a very few countries.

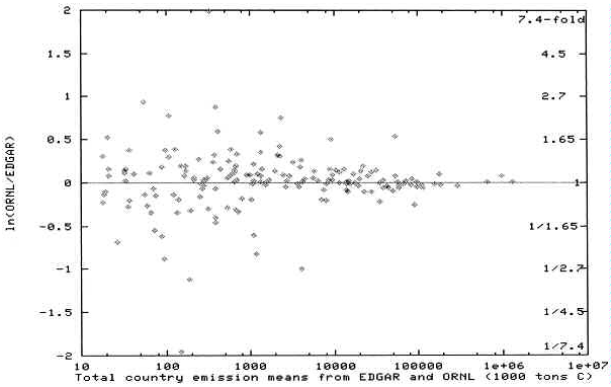

Fig. 2. Country total emissions.

In searching for a suitable numeric to compare national estimates over this large range of values we find the logarithm of the ratio of the two emissions estimates to be useful. The log of the ratio has the properties such that it is zero when the two values are exactly the same and it is symmetric about zero when the two values differ by a common factor, i.e. one value is double or half the other value. Using the logarithm produces a scale that lets us see both the small and large differences. By plotting the log of the ratio against the mean of the two values (Fig. 2) we can see the relative magnitude of the two estimates against their absolute value. With the highest emissions for any country, the point for the US thus falls furthest to the right in Fig. 2 (the mean of the ORNL and EDGAR estimates is plotted on the x axis) while the small positive value on the y axis shows that the two estimates are very close and that the ORNL value is slightly larger. Being concerned with both the absolute and relative magnitude of estimates, note that the second point from the right in Fig. 2 represents emissions from the USSR, a single reporting entity in 1990.

Table 1. The difference between the ORNL and EDGAR estimates of national CO_2 emissions for the ten countries with the largest absolute differences (in millions of tons of carbon)

Country	Absolute difference	Percentage difference[a]
USSR	78.7	8.1
North Korea	27.8	52.2
South Africa	23.0	25.3
India	17.6	9.9
USA	11.8	0.9
Japan	10.0	3.4
Venezuela	7.5	21.5
Canada	6.1	5.3
China	5.4	0.8
Taiwan	4.7	15.0

[a]Percentage difference is defined here as the difference between the two emissions estimates divided by the mean of the two estimates and multiplied by 100.

Casual observation of Fig. 2 suggests that the values cluster about and are symmetric about the zero point on the y axis and that the scatter increases as the absolute magnitude of emissions decreases. Symmetry about the zero point suggests that there is no systematic bias whereby one set of estimates is consistently larger or smaller than the other. Table 2 shows that the plot of Fig. 2 includes comparisons for 173 countries, where both ORNL and EDGAR provide non-zero estimates of CO_2 emissions, and that there is a slight tendency for the ORNL value to be larger (the mean of the logs is positive). Recall that the ORNL values include emissions from domestic aircraft while the EDGAR values do not, so a small positive bias is our initial expectation. All logarithms here are natural logs so 1 unit on the y axis in Fig. 2 implies that the two estimates differ by a factor of 2.72 while ±0.5 indicates that they differ by a factor of 1.65 (one value is 65% larger than the other) and 20.22 indicates that they differ by a factor of 1.25.

Fig. 2 is for total CO_2 emissions from the respective countries. We can separate this into the primary components and replicate the analysis. Fig. 3 shows national emissions from gas flaring with the log of the ORNL/EDGAR ratio plotted against the mean value of national total emissions, as in Fig. 2. Fig. 3 shows very good agreement for most countries with a small bias toward higher values in the ORNL estimates. Fig. 4 provides a similar comparison for emissions from cement manufacture and again confirms the similarity

Table 2. Comparison of ORNL and EDGAR estimates of national CO_2 emissions for the various fuel groups and for three groups of countries grouped according to the magnitude of their emissions; statistics are for values of Ln (ORNL/EDGAR)

Ln (ORNL/EDGAR)	Mean	Std dev	Number of countries	Percentage of global total emissions
All countries				
***Total* emissions**	0.011	0.449	173	
***Solids* combustion**	−0.161	0.921	92	
***Gas* combustion**	−0.042	0.621	74	
***Liquids* combustion**	0.107	0.391	170	
***Cement* production**	0.016	0.207	123	
Flaring	0.027	0.050	40	
***Total emissions* selected countries**				
***Highest* emitting countries**	0.010	0.115	48	93.7
***Medium* emitting countries**	0.093	0.259	41	5.2
***Least* emitting countries**	−0.028	0.611	84	1.2

of estimates for most countries. Nevertheless, it is clear that the US Bureau of Mines and UN-based numbers differ substantially for a number of countries.

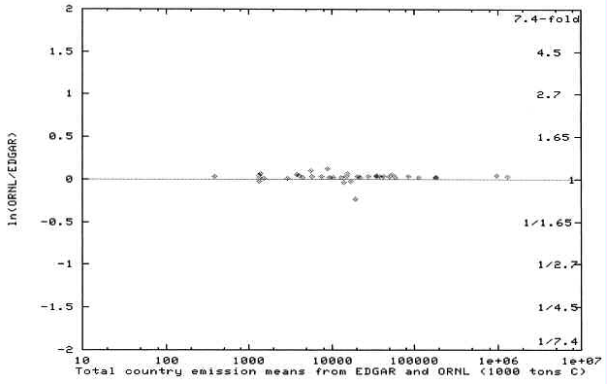

Fig. 3. Country flaring emissions.

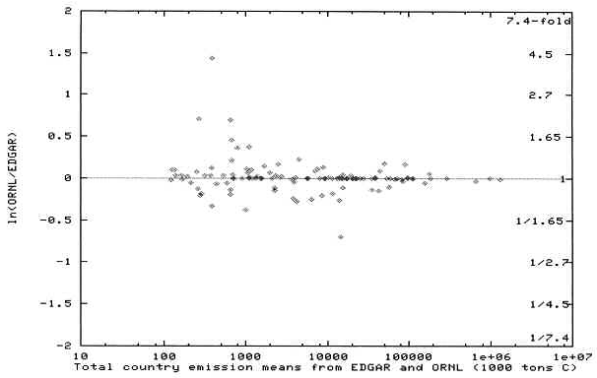

Fig. 4. Country cement production emissions.

Emissions from gas flaring and cement manufacture account for only a small portion of emissions, however, and it is in the fuel accounts of Figs. 5-7 that we see the majority of total CO_2 emissions and the origin of the differences between the two sets of estimates. Table 2 reports the mean and standard deviation for values of log (ORNL/EDGAR) (again the natural log) and confirms that the differences are smallest for cement production (mean value 0.016) and largest for solid fuels (mean value -0.161). The spread of values is also greatest for solid fuels (standard deviation 0.921). For solid and gaseous fuels the EDGAR values tend to be slightly higher (negative values for the mean of the log). The treatment of international aircraft fuels presumably contributes slightly to the higher values for ORNL for liquid fuels (positive value for mean of the log). Examination of Fig. 2 suggests that the scatter of values increases as the magnitude of the emissions decreases and we tested this by separating the coun-

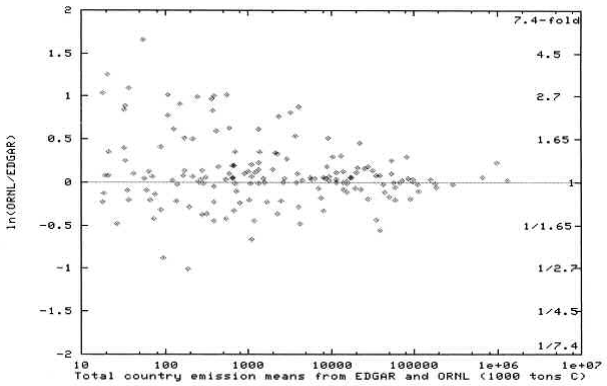

Fig. 5. Country solid combustion emissions.

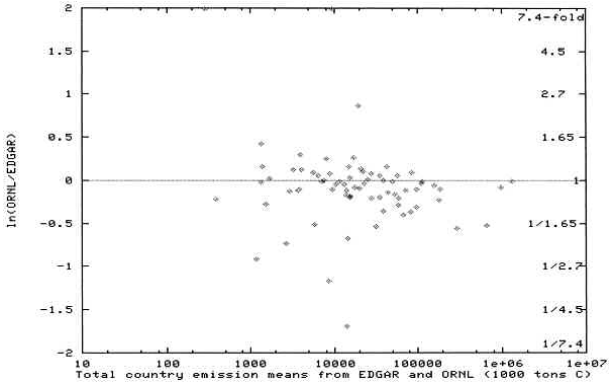

Fig. 6. Country liquid combustion emissions.

Table 3. Comparison of ORNL and EDGAR estimates of national CO_2 emissions for countries in ten regional groupings. Regions are in order of decreasing values for the standard deviation for values of Ln (ORNL/EDGAR); mean is for values of Ln (ORNL/EDGAR)

Ln (ORNL/EDGAR) statistics	Mean	Std dev	Number of countries	Percentage of global total emissions
Regions				
Africa (AFR)	−0.070	0.727	52	3.1
Far East (FEA)	0.066	0.313	21	7.3
Central and South America (AMD)	0.003	0.295	37	4.7
Centrally Planned Asia (CPA)	0.276	0.244	4	12.6
Oceania (OCN)	0.137	0.240	20	6.4
Middle East (MDE)	0.054	0.116	15	3.9
Western Europe (WEU)	−0.025	0.084	19	11.0
Eastern Europe (CPE)	0.001	0.053	7	21.4
North America (NAM)	0.000	0.050	3	25.0
Germany (GER)	−0.020	0.003	2	4.6

tries into three groups according to the magnitude of national CO_2 emissions. The 48 top-emitting countries are those with total emissions greater than or equal to 1% of the emissions from the largest emitting country (the US) and the medium emitting countries are those with emissions between 0.1 and 1.0% of the US value. Table 2 confirms that the relative difference between the ORNL and EDGAR values is largest for the smallest countries. With 93.7% of global CO_2 emissions being discharged from these 48 top emitting countries, it is clear that the match of the two estimates is quite good here (standard deviation = 0.115; implying a mean difference on the order of 12%) and that the global statistic is degraded by poorer matches in countries that contribute little to total emissions. Although no systematic bias is evident, the means of the logs shows that EDGAR estimates are inclined to be the higher for small countries whereas the ORNL values are higher for the other 2 classes. Looking for indications of regional differences in data quality or consistency, we have made similar calculations for 10 geographic regions (Table 3). Table 3 shows, not surprisingly, that the difference between the ORNL and EDGAR estimates are largest for Africa. Reporting of energy statistics to the UN Statistics Office tends to be inconsistent, and often non-existent, from many African countries and the UN and IEA are driven to sources outside of their formal reporting. EDGAR estimates tend to be higher than ORNL for Africa and Western Europe while ORNL values are higher for the other world regions.

To summarize, this comparison of the ORNL and EDGAR estimates of national CO_2 emissions indicates that at the mean of all country differences the two sets of estimates differ by about 1%, but this includes 17 countries where they differ by a factor of 1.65 or more. The fractional differences tend to be greatest for countries with smaller emissions, especially those from Africa. But for the larger emitting countries even small relative differences can be very large in absolute terms. The two sets of estimates correlate very strongly and it is easy to focus on those countries where large discrepancies occur. At this point we have not attempted to delve into the detailed energy statistics but point out that two ostensibly similar efforts to estimate national CO_2 emissions using ostensibly similar international energy statistics have produced results that differ significantly for many countries. However, the differences in estimated CO_2 emissions are not entirely due to national collection and processing of energy statistics. As an example, for Western Europe, where energy statistics are of high quality and both the UN and IEA data sets derive from the same IEA questionnaire, Table 3 shows small differences that must be attributed to data processing in the international agencies and conversion to CO2 emissions estimates by ORNL and EDGAR analysts. The small spread of values and small positive bias for estimates of CO2 from gas flaring (Fig. 3 and Table 2) suggest a bias in the emissions coefficients used by ORNL and EDGAR. But for the other comparisons the divergences appear too large and unbiased to be attributable to emissions coefficients and must be attributed to the estimates of fuel consumption. (See also Table 4.) There do not appear to be large systematic differences in the two data sets and the differences that are important at the national level are averaged out in the aggregate. Improved collection and reporting of energy statistics from many countries will be required to achieve a more consistent set of national emissions estimates, but the uncertainties in the global total depend on the treatment of data from only a hand-full of countries.

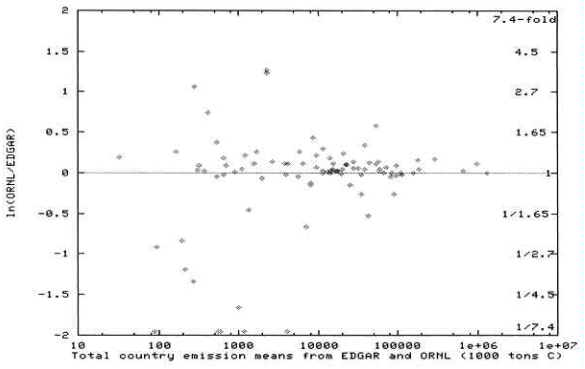

Fig. 7. Country gas combustion emissions.

Table 4. Summary of key inputs to the ORNL and EDGAR CO_2 emissions estimates

	ORNL	EDGAR
Energy data		
– data source	UN	IEA
– fuel consumption	primary solids, liquids, gases	detailed fuel types by end-use sector
– units for primary data	ton, TJ	TJ (LHV) (converted using country specific conversion factors)
– sources	all domestic use for combustion	similar (on grid: minus domestic aircraft)
Cement data		
– data source	US-BoM	UN
– variable	cement production	cement production
Gas flaring data		
– data source	UN	IEA
Emission factors		
– for fuel combustion	3 uniform aggregated values	essentially the same values
– correction for unoxidized part	yes	no
– for cement	uniform factor	same value
– for flaring	uniform factor	same value

While this analysis tells us little about how accurately international statistics report global fuel consumption or which statistical source more accurately represents reality, it does tell us that conscientious data management can still yield quite different estimates of fuel use in many countries.

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6.3 Validation and verification of national inventories

This discussion paper was prepared for the IPCC Expert Group Meeting '*Cross-Sectoral Methodologies for Uncertainty Estimation and Inventory Quality*', Culham (UK), 5-7 October 1999, and will be published as:
Olivier, J.G.J., Winiwarter, W. and C.-P. Chang (2002) Checks and verification at national and international level. In: IPCC (ed.) *Papers prepared for the IPCC Expert meetings on Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. IPCC National Greenhouse Gas Inventories Programme, TSU, IGES, Hayama, Kanagawa, Japan.

Abstract
National inventories submitted under the UN Framework Convention on Climate Change are updated annually, i.e. the inventory for a new year is compiled and added and the emissions of the other inventory years are being revised when considered appropriate. Since this process requires the handling of much data and often many persons are involved, both in selecting representative emission factors as well data processing, errors and inconsistencies may easily slip in. This paper reviews the needs and possibilities for validation (checking) and verifying procedures, i.e. checking the internal consistency of the inventory and activities using external data to verify the emission estimates, respectively. Concrete options are reviewed that could typically be done at national level, by national teams, and options at the international level that comprise for example inter-country comparisons and comparisons with independently compiled datasets (global emission inventories and international statistics). The latter could most efficiently be done at international level by international bodies or by international co-operation of national experts. In this paper we will primarily focus on what individual countries can do. In addition, procedures, priority setting and reporting requirements of checks and verification activities at national level are being discussed, as well as possible institutional arrangements for activities at international level.

1. INTRODUCTION

1.1. The inventory compilation process

Emission inventories may be compiled for a special purpose as a one-time activity. In order to monitor environmental progress, however, periodic updates of these inventories are needed. Under the *Kyoto Protocol* of the *UN Framework Convention on Climate Change* (UNFCCC) countries are required to submit an update of their greenhouse gas emission inventory to the Climate Change secretariat annually. In year *t* the inventory should contain final figures for the years 1990 up to *t-2* inclusive and preliminary emissions for the year *t-1*. There is no need to re-submit final emission data for older years, unless these data have been changed (e.g. due to recalculations, re-allocations or addition of new sources). Any extension or update of existing inventories will build on the existing one: addition of a year, finalisation of preliminary previous year, possible adjustments of so-called final historical years ('recalculation'). In addition to emission figures, the inventories prepared for the UNFCCC should also include information on the uncertainty estimate for the reported figures.

So, following the activities that take place annually, the annual inventory update process can be split into four parts, building on the existing historical inventory in place (including estimated uncertainties) which has been the result of last year's activities, on a source by source basis:

1. New additions to the emission inventory (new year[s], possibly new sources);
2. Finalisation of last year's preliminary data;
3. Adjustments to the existing inventory (e.g. recalculation) (if applicable);
4. (Re-)evaluation of the estimated uncertainties.

It is this sequel of activities that also provides many opportunities for carrying out internal checks at various stages of the update process.

1.2. The need for checking and verification

Because of the many data and many institutes involved in the emission inventory compilation, as well as – ultimately – in the judgement of representativity of emission factors, small or large errors and inconsistencies (e.g. across sources or in time) may easily slip in. Therefore, checking and verification procedures are important and indispensable elements of the Quality Assurance/Quality Control (QA/QC) system of the inventory management (IPCC, 2000).

Checking is part of the validation of the inventory, which involves checking to ensure that the inventory has been compiled correctly: calculations have been done correctly and in line with guidelines and reporting instructions. Thus *validation* refers to *internal checks* of the consistency of the inventory. *Verification,* on the other hand, refers to activities using *external data* that help to establish the reliability for the intended applications of the inventory: external methods to check the truth of the inventory include comparisons with refer-

ence calculations, with estimates made by other bodies, with atmospheric concentrations or external review.

This paper aims at presenting concrete options for the internal checking and verifying national greenhouse gas inventories. For each of the components of the inventory process we will describe readily available techniques for performing quick basic checks on apparent errors (order-of-magnitude checks), completeness, consistency, and comparability. This paper will present the practical checks and verification procedures that we recommend to be taken. Using the instructions given, a system can be established for priority setting and for reporting the checks and verification activities performed and their results (see especially Section 5). In addition, we will discuss other, more elaborate methods of verifying the inventory on these aspects thoroughly, which are beyond the scope of inventory guidelines at this time.

2. DATA QUALITY OBJECTIVES

In order to provide confidence to the inventory system, the establishment of high quality data is indispensable. An inventory system becomes useful in the international context only if it may be proven to meet the objectives it has been devised for - objectives as defined in the 'data quality objectives'. For national and international (UNFCCC) purposes of establishing credibility of the national inventories, the UNFCCC preparation guidelines describe the data quality to be achieved in terms of accuracy and the three C's: Completeness, Consistency and Comparability. Accuracy refers to emissions being calculated correctly and unbiased - as far as can be judged - and uncertainties being reduced as far as practicable. This calls for identification and correction of apparent errors in input and calculation (e.g. order-of-magnitude checks) and for efforts being made to reduce the largest uncertainties. Completeness means that all relevant sources are included in the inventory. Consistency means that per source category for all years the emissions are calculated with the same emission calculation methodology and for all years the same source definition (allocation) is used. Comparability means that the emission inventories are comparable across countries. This refers to both emissions and the estimated uncertainty. Emissions of two countries are called comparable if they use the same source definitions, similar emission calculation methodologies and similar emission factors in similar cases. Therefore, they can also be considered comparable if for major national sources the calculated aggregated ('implied') emission factors are well within the estimated uncertainty or if large deviations from others (a set of factors reported by a group of apparently 'similar' countries, or - if these are not available - IPCC defaults) are clarified and justified. In other words, verifying comparability requires checking for and documenting of observed seemingly deviating figures for (aggregated) emission factors.

From the description given above it shows that for checking comparability it is required that emission data compiled at the international level are being made available either by independent organisations or by the UNFCCC Secretariat. Individual countries can perform this type of verification, but also other organisations as well as individual scientists. In this paper we will primarily focus on what individual countries can do.

3. OVERVIEW OF OPTIONS ON THE NATIONAL SCALE

3.1. Approaches in relation to data quality objectives

A number of approaches have been identified for quality control of elements for which the UNFCCC has defined its objectives (EEA, 1997; Lim et al, 1999; Van Amstel et al., 1999):

1. internal quality checks (comparison between years and inventory versions);
2. inventory inter-comparisons (comparison with other independently compiled estimates, with national inventories of other but similar countries and with IPCC defaults);
3. comparison of density indicators;
4. verification by comparison with direct atmospheric concentration measurements;
5. comparison with atmospheric budgets derived from atmospheric models;
6. direct source testing (on site measurement of large emission sources).

The degree to which they check or independently verify the inventory varies between approaches – as does the capacity required to perform these activities. Therefore, we will distinguish between the more easy, less elaborate ones, referred to as 'checks' (either internal or using external data), and more complex, data intensive, time-consuming activities, referred to as 'verification'. For example, direct source testing is a means of ground truth verification, which however will often not be simple to perform. In addition, for practical reasons we will also distinguish between options using national data only and options which require the availability of international data. Based on the mentioned approaches a number of options have been identified, which are described in more detail in separate sections: options for (a) checking and (b) verification using national data, and (c) options using international data.

3.2. Options for checking

In the field of the present paper, the checks at national level considered here relate to checks to be performed

when the inventory is finished (as draft or final version). So compared to the QC processes, the same checking methods may be used. The differences arise from the fact that the QC processes include larger checks (e.g. data management system controls) and start from the beginning of the inventory preparation as described in IPCC (2000). With respect to this matter, we can wonder whether these considered checks at national level are part of QC processes or not. A first reply could be 'yes', in the case it is done by the national inventory team, but 'no', if it is performed by an external team or organisation. To illustrate the point, we can give the example of related practices with CORINAIR inventories. In case of CORINAIR inventories managed by the European Environment Agency (EEA), after national inventory checks, national individual checks are also performed by the ETC/AE (European Topic Centre on Air Emissions) [now merged into: ETC on Air and Climate Change, ETC/ACC]. But it is time (and effort) consuming, especially when there are feedback processes and successive national reviews. So the tendency no longer is to perform at the ETC detailed individual checks, but to expect efforts from national QA/QC processes. There are a number of options to perform quick basic checks on new figures using the existing inventory that has already been quality assured and other means:

- *Comparison of trends and with previous reported data* (emissions, but can also be applied to activity levels and emission factors).
  Purpose: consistency and completeness check.
- *Checking for and documenting any methodological changes in the components of the inventory* (activity data, emission factors, emission calculation methodology).
  Purpose: consistency check; documenting and justifying data and methods used.
- *Order-of-magnitude checks* (e.g. by comparison with IPCC Tier 1 calculations using IPCC default factors or by comparing an activity to a related one).
  Purpose: quick indirect check for possible major calculation errors and inclusion of major sources.
- *Reference calculation, such as for CO_2* (based on apparent consumption).
  Purpose: top-down vs. bottom-up comparison to ensure completeness and right order-of-magnitude, in the case of an inventory based on a bottom-up approach.
- *Checking estimated uncertainties*
  Purpose: check the order-of-magnitude of the estimated uncertainty for possible errors in input or calculation and for apparent country-specific uncertainty levels in either activity data or emission factors.

3.2.1 Comparison of trends and previous reported data

A consistency and completeness check using the available historical inventory data for multiple years is based on the experience that the emission level of most sources does not abruptly change from year to year, due to gradual changes in both activity levels and emission factors, if any. In most circumstances the change in emissions will be less than 10% per year. Thus percentage changes of emissions in year *t* compared with year *t-1* are a good indicator of possible input or calculation errors. An additional result of this basic consistency check is - except for correction of identified errors resulting in large differences - that it automatically identifies the areas in the inventory which call for a clarification if not justification.

In case of important emission changes between year *t-1* and *t*, and especially in case of major emission contributing sources, further checks with trends from historical data can be performed respectively for activity rates and emission factors. For example, historical trend analysis on activity data can help the activity checks by comparing the historical activity trend up to the last inventory, with an expected activity trend, or with the trend of a related and correlated indicator. For emission factor trend checks, the historical emission factor for a given pollutant and sector, can be compared to an expected trend (e.g. from an external expert in the given sector) due to technology evolution or other reasons.

Another routine check that can be made with the newly finalised data for a year *t*, provided that the previous version of the inventory contains *preliminary* figures for that year *t*, is inspection of the difference between the final and the preliminary figures. The actual checking process is identical with the checking of differences between subsequent years, but it is a qualitatively other type of check, since it checks both the accuracy of the newly finalised data and utilises source-specific knowledge about the likely trend in it. Moreover, it provides a review of the quality of the estimation procedure for the reported 'preliminary emissions'.

<u>Phase in compilation process and update types</u>
Routine checks using the internal consistency of the inventory may be applied at three points in time in the inventory update process:

A. Draft sectoral inventories: per sector, per gas;
B. Final sectoral inventories: per sector, per gas;
C. Final inventory: per gas, total inventory, main source sectors.

The term 'draft' or 'final' may apply to all parts of the update process:
(1) newly finalised emissions for year *t* (in previous version possibly labelled as 'preliminary'): com-

parison with previous year's emissions (i.e. in year *t-1*) *and* with the 'preliminary' emissions for year *t* in last year's version of the inventory (if available);
(2) new preliminary emissions for a year *t+1*: comparison with previous year's emissions (i.e. year *t*);
(3) revisions of older 'final' emissions: comparison both with previous year's emissions *and* with emissions in last year's version of the inventory.

Procedure for routine consistency checks
1. Standard checks (see example below);
2. Standard actions (log of check; correction of data or explanation of differences);
3. In case of corrections: re-apply standard checks for corrected parts + standard actions.

After calculation of differences, the largest percentage differences (in any direction) can be flagged, either by visual inspection of the list, or visual inspection of graphical presentation of differences (e.g. in a spreadsheet) or by using a dedicated software programme that puts flags and rankings to the list of differences. When dealing with very many sub-sources graphical presentation of differences is a very efficient tool to get an overview of the differences for all sources and to point out the sources with the largest differences. If all data are available electronically, these checks could be done for all sub-categories available without much additional effort. Possibly erroneous results could be flagged e.g. using a dedicated programme or screening the results.

Example of routine consistency check (applicable to any of the points A-C and update types 1-3):
Check annual increase/decrease of emissions per subsector available in the inventory, expressed as percentage [figures and percentages used to be evaluated by the individual country according to priorities and national experience]:

1. *Check the five largest percentage differences for arithmetic errors:* Check the cause of difference and either correct or explain the differences; if differences are larger than 10% and appear to be correct then justify the figures.
   When explaining or justifying observed large differences, one should keep in mind that for more aggregate sectors less change is expected than for sub-sectors. For example, total emissions from petrol cars are not likely to change substantially on an annual basis, but emissions from sub-categories, such as catalyst-equipped petrol cars, may show substantial changes if their market share is not in equilibrium or average technology applied changes quickly.
2. *In addition, check all cases with differences larger than 10% for arithmetic errors:*
   If considered important for the source category or the quality of the update process, one could extend the check to all cases that show differences of over 10%. However, here too, one should keep in mind that annual differences in minor sub-sectors may be larger than in higher aggregates.

Causes to be checked
Possible causes of major differences are:

1. *printing or arithmetic errors in statistical and emission factor data used:*
   To be checked by comparing with the values used for the previous year (data at this level can also be routinely checked by systematic comparison with the values used for the previous year as described for the resulting emissions). If these do not differ much, than the following checks should be made:
   - input errors (to be checked by comparing input data with the external source of the activity level and emission factor);
   - arithmetic errors (to be checked by recalculation).
2. *large discontinuities in calculation methodology or source definition:*
   To be checked for if the first check on printing or arithmetic errors does not provide sufficient clarification of large annual changes:
   - substantial changes (discontinuity) in methodology for establishing the annual activity level for a specific category (to be checked with the agency that compiled the statistics);
   - discontinuities due to a change of source definitions (may be related to methodological changes too). This may show up as a shift between two or more sub-categories, one increasing and other(s) decreasing, while the change in the total remains small. Examples are: different inclusions of off-road vehicles, cogeneration (CHP), some 'miscellaneous' categories (to be checked by asking the people or organisation, which actually did the emission calculation, or the organisation that coordinates the overall inventory process for any changes of this nature).
3. *in case of comparison with preliminary figures: unexpected actual developments in the source:*
   Differences can be caused by either a trend estimation methodology for preliminary figures that appears to be too simple to capture the real developments of the source or by unexpected developments in the past that the estimators were not aware of at the time when the preliminary estimate was made.
4. *in case of revisions of older 'final' emissions:*
   Differences may be caused by any change in underlying activity data, emission factors or emission calculation methodology. Good practice is to report (a) for which gases and sectors figures are changed compared to last year's release of the inventory, (b)

the size of the largest changes, (c) the cause of these changes, and (d) justification of the largest changes.

3.2.2 Checking for methodological changes

For reasons of transparency and consistency, any methodological changes in the components of the inventory compared to the last year's version, either in the existing final inventory or in the new or newly finalised parts, should be checked for and reported: activity data, emission factors, emission calculation methodology. Large changes in any of these should have been identified already in the previous checks of trends and of different versions. In addition, the organisations or people actually doing the sectoral emission calculations should be asked to document and justify any change in data and methods used. In particular, when source definitions have been changed it should be checked that neither overlap nor gap has been created (e.g. check of proper co-ordination between the sector groups).

3.2.3 Order-of-magnitude checks

This type of quick check for possible major calculation errors and inclusion of major sources is particularly valuable if the emissions have been calculated as the sum of many individual sub-sources (e.g. many point sources in industry and energy sectors or many subcategories of road transport). Then comparison of emissions with a top-down approach e.g. IPCC Tier 1 calculations using national total statistics as activity data and IPCC default factors is a possible check. For an example of this comparison for the UK inventory see Salway (1998). In case of major discrepancies between the emissions, as a further check the underlying sum of activities or the weighted average emission factors can be compared. In some cases another basic check is to compare the emissions with a country of seemingly similar characteristics and size (cf. options involving international data, item 3.4 and 4.1.1).

Comparing the activity of one type to another is a further type of order-of-magnitude check that can be made. Examples are: calculation of average annual fuel consumption per car by dividing total fuel consumption of road transport by the number of cars, dividing total production of animal manure by the total number of livestock, total amount of waste produced by the number inhabitants. If these do not relate to sensible figures per car, per animal or per person, than this is an indication of an input or calculation error.

3.2.4 Reference calculations

In a number of cases where emissions are calculated as the sum of sectoral activities based on consumption of a specific commodity, e.g. fuels or products like HFCs, PFCs or SF_6, the emissions could alternatively be estimated using apparent consumption figures: national total production + import - export ± stock changes. For CO_2 from fossil fuel combustion a reference calculation based on apparent fuel consumption per fuel type is mandatory according to the IPCC Guidelines. Also in other cases where the inventory is based on a bottom-up approach, a top-down versus bottom-up comparison of activity data is an efficient check of completeness and order-of-magnitude of this part of the inventory.

3.2.5 Checking estimated uncertainties

Irrespective of the Tier used for estimating uncertainty in reported emissions, it is Good Practice to compare the quantitative national results for the main source categories with the order of magnitude uncertainty indicator resulting from using the IPCC Tier 1 default uncertainties (as provided in the *Good Practice Guidance* report (IPCC, 2000) for specific sectoral emissions).

If the results per main sector or for the country total are very much different, a calculation or input error could have occurred in estimating the sectoral uncertainty per gas or the national total per gas. In those cases it is recommended to check whether country-specific uncertainties in key parts of the inventory are indeed much different to the IPCC defaults for Tier 1. If that is the case, it is Good Practice to document the references for the uncertainties used as input for the calculation of these sectoral uncertainties well. If inspection shows that the country-specific uncertainties in key parts of the inventory are not quite so different, then it is Good Practice to do a check on inputs and calculation.

3.3. Options for verification at national level

In some countries there may be more institutes estimating greenhouse gas emissions, thus producing complete or partial inventories that have been compiled independently, with their own choice of data sources and methodologies. Comparison of the official national inventory with these independently compiled other estimates provides a quick check for apparent errors such as lack of completeness and incorrect source allocation. More elaborate options at the national level take advantage of data as independent from the inventory as possible. Such data can be derived from actual measurements. Climate gases generally are characterised by a long half-life in the atmosphere. As a consequence, their typical atmospheric concentrations are relatively stable. Increments due to sources thus are relatively small compared to a background concentration. The challenge in identifying the contribution of a source or source area is to identify a minute increase over a stable baseline. In order to assess the maximum increase possible, one may wish to obtain the possibly strongest signal, which is obviously very close to a source: Direct source testing involves local measurement of key parameters as a means of

ground truth verification of key sources. Comparison with atmospheric measurements at national scale serves as independent, ground truth verification of annual emission levels and, possibly, emission trends. Other options for verification are comparisons with estimates published in scientific literature, based on a review of the nationally available literature. Also publications analysing the quality of the official national inventory may be used in this respect.

3.3.1 Comparison with other national data

Comparisons with other, independently compiled, national emissions data for the country are a quick option to verify completeness, approximate emission level and correct source allocation – if such an independent inventory is available. It can be made per compound at national, sectoral and sub-sectoral level, as far as the differences in definitions/sectoral nomenclatures enable it. Procedures to be taken resemble those of comparisons with international data. Thus we refer to Section 3.4 for more details.

3.3.2 Direct source testing

The following approaches for direct source testing have been used previously:

- *On-line stack measurements*
  Already now, many major power plants are equipped with routine monitoring equipment for CO_2 measurements. While this instrumentation helps maintain combustion conditions, usually the C content of fuels is considered a more reliable indicator for CO_2 emissions.
- *In-plume measurements*
  The in-plume freight of a constituent may be estimated from its concentration in a cross section and the transport velocity. Emission estimates of this kind have been made to assess volcanic CO_2 emissions (Allard *et al.*, 1991) or conventional pollutants in city plumes (Klemm and Ziomas, 1998), which however already include a multitude of single sources.
- *Remote measurements*
  Open-path FTIR spectroscopy has been successfully shown to assess SF_6 (Hashmonay *et al.*, 1999) and NH_3 emissions of diffuse area sources, but it also has high potential for CO_2, CH_4, N_2O and other gases (Schäfer *et al.*, 1999). Results are obtained with the help of inverse dispersion modelling to reconstruct emissions from concentration measurements.
- *Indirect methods*
  Using a tracer (or adding a tracer to the plume of a stack) allows to the identification of even small amounts of a compound, once the ratio between the compound and the tracer is known and there is sufficient reason to believe that they behave identically during atmospheric transport. The method applied has been used to identify SO_2 emissions from power plants by adding deuterated methane as tracer (Malm *et al.*, 1990).

All these approaches allow the direct attribution of observed concentrations to the emissions from a certain source. However they do not allow for a complete coverage of a country, as normally only a small part of the emission sources of a country can actually be measured. Especially assessment of area emissions is very laborious and costly, and in practice will only be done to obtain emission factors – maybe with the exception of rare and single sources as volcanoes. In cases when it is unsure if general emission factors may be applied to a certain country, measurement of this kind are advisable. In direct source testing, uncertainty of measurements (including the associated steps for emission calculation, like model uncertainties) are considered to be as low or lower than the uncertainty in the emission inventory. Therefore results may be used to reduce total inventory uncertainty.

3.3.3. Comparisons with atmospheric measurements

The processes between emissions and ambient concentrations are complex even for climate gases, which do not easily undergo conversion processes. Still at a given site, background concentrations may be assessed from the low concentration levels, and enhanced concentrations (plumes) from high levels. Under certain circumstances, emissions may be considered proportional already to the difference between such low and high levels. Nevertheless, the use of an atmospheric model should be advised in order to adjust for the dilution and deposition processes, and also to cover transport direction. Measurements are to be performed on one or several fixed sites. One option is to compare measured concentrations with modelled concentrations. In terms of emission assessment it seems more appropriate however to perform inverse modelling, i.e. estimate emissions from measured concentrations.

Clearly, in comparison to the direct source testing the signal-to-background ratio may prove to be an even stronger challenge. This may be overcome for climate gases that do not have so high background concentrations (SF_6, CFCs), or by using markers within compounds, which differ strongly to the background. Such markers can be stable isotopes, which occur in different abundance in the background and in the emission source. These markers (^{13}C) have been used for assessing CH_4 emissions (Levin *et al.*, 1999). Theoretically, also application on ^{15}N (in N_2O) is possible, as has been shown for NH_3 (Bruckner *et al.*, 1996). As e.g. the abundance of ^{13}C is not only different between background and emissions, but also between different emission sources, conclusions may be drawn on the relative contribution of each such source to the total.

The applicability of such methods obviously is not limited to areas defined by national boundaries, but rather to areas that are characterised by elevated source strength, as it is only possible to differentiate areas of differing emissions strengths. As industrial and population centres are frequently situated at both sides of a national boundary, however, an evaluation for just one country is not possible because emissions can only be assessed for the whole area. In such a case, the methods become valuable only on a bilateral or international level.

In practice, due to the limitations, uncertainty associated with measurements and inverse modelling may become rather high, and a careful evaluation of the measurement/model system uncertainty with respect to the inventory uncertainty becomes essential [see Chapter 'Quantifying uncertainties in practice' in IPCC (2000)]. When performing a significance test, the following results are possible:

1. Measurement/model results are significantly different to the inventory
   → Falsification of the inventory; sources are missing, inadequate emission factors or statistics used, calculation error
2. Measurement and inventory do not differ significantly, uncertainty of measurement is lower than uncertainty of inventory
   → Measurement results may be used to reduce inventory uncertainty
3. Measurement and inventory do not differ significantly, uncertainty of measurement is higher than uncertainty of inventory
   → Measurement results are not useful in terms of the inventory, except that it confirms previous assumptions on completeness and lack of errors.

3.3.4. Comparison with scientific publications and external review

Although the government is responsible for the compilation and submission of the national greenhouse gas inventory, there may be other independent publications about the same subject e.g. published in scientific literature. This provides another option for comparison with other national estimates. Also publications analysing the quality of the official national inventory may be used in this respect. While scientists are basically limited to the methods described above, results may be already available. In practice such a comparison means to review the nationally available literature and compare data on paper. The review report should document the results of the comparison and be included in the report on QC activities performed. In addition, external review of the national inventory, either peer review commissioned by the compilation agency or public review encouraged by the agency, is an opportunity to compare methods and data used by the inventory preparation agency with the judgement of scientific experts or stakeholders and others with specific knowledge in this field.

3.4. Options for verification involving international data

There are several different comparisons that can be performed using international data:

- *Comparison of emission density indicators with similar countries* (e.g. emissions per capita; industrial emissions per $ of value added; transport emissions per car; emissions from power generation per kWh of electricity produced by fuel type (coal, oil, gas) (excluding cogeneration), etc.)
  Purpose: quick indirect check and verification
- *Performing comparisons of emissions with other estimates: with independently compiled authoritative estimates* (international datasets e.g. from IEA, CDIAC, GEIA/EDGAR or WRI)
  Purpose: checking completeness, consistency, correct source allocation, order-of-magnitude
- *Comparisons of emission factors:*
  - with IPCC defaults
  - with literature values
  - with those used by similar countries
  - with the set of implied factors reported to UNFCCC (as proposed in the 'Common Reporting Format', CRF)

  Purpose: checking comparability and country-specificity
- *Comparisons of activity data:*
  - with independently compiled estimates (e.g. from IEA, UN, FAO)
  - with activity density indicators from similar countries (e.g. activity rate per inhabitant, per employee, per unit of gross domestic product (GDP), per number of households or per number of vehicles, etc., according to the source sectors)

  Purpose: checking completeness; order-of-magnitude check
- *Comparisons of uncertainty estimates of data reported to UNFCCC*
  Purpose: checking order of magnitude of own uncertainty estimates against others

It will be clear that for a given source, different parallel comparisons can be performed:

- comparisons with other independently compiled emissions data for the specific country: checking completeness, magnitude, and proper source allocation.
- inter-country comparisons: for a specific year, the comparison of background data (activity levels,

aggregated emission factors or other factors used in the methodology) from the different countries.

The first kind of *comparison with other estimates* for the country under investigation is a quick check for completeness, approximate emission level and correct source allocation. It can be made per compound at national, sectoral and sub-sectoral level, as far as the differences in definitions/sectoral nomenclatures enable it. In Section 4.1.1 examples of reference databases are presented. If large discrepancies show this does not necessarily mean that one or both inventories contains flaws, but rather points to possible inadvertent errors, which are also aspects of uncertainty within inventories that can only be evaluated using this method. In those cases, one may wish to do a further check on activity levels or emission factors in that sector. In case of large differences for sub-sectors, one should also be aware that in either inventory the sum of the subsources might well be comparable by hiding shifts of part of the emissions between these sectors. Comparison with reference inventories developed by other authoritative sources is also a check of the comparability, when the reference inventory uses a common methodology for all countries. If these inventories have calculated national emissions using the Tier 1 methodologies of the *Revised 1996 IPCC Guidelines* (IPCC, 1997) then comparing emissions means automatically also a check against the default emission factors recommended by IPCC - if activity levels used in the reference dataset are similar to national data.

Concerning the latter kind of *inter-country comparison* of emissions, emission density, reported or background emission factors, activity or activity density, such checks can be based on reported results from international checks (cf. options on the international scale, item 4.1.1) but with a delay in time, or based on national initiatives to get/calculate such data/density indicators for the more recent inventoried year and for the other countries. The inter-country comparison of reported aggregated emission factors could be combined by plotting in a single graph: for the different countries, the reference year data (1990), the more recent year data, and the minimum and maximum value, for each source sector and possible aggregations and according to the fuel types when relevant (see Figure 6.1). The comparison of data is relevant if the data are comparable. Consistency checks of trends in emission factors at national level and cross-country comparisons of emission factors can be processed as far as units are fixed (there are a few exceptions). These can be based on the sectoral background tables of the 'Common Reporting Format' (CRF) trend. Thus, comparisons of (aggregated) emission factors can be made with the set of implied factors reported to UNFCCC (as proposed in the 'Common Reporting Format', CRF). If some national emission factors appear to be outliers, further comparison could be made by checking with those used by apparently similar countries. Furthermore comparison with the recommended IPCC Tier I default values and with literature values may be informative in establishing the comparability or the country-specificity of the emission factors used.

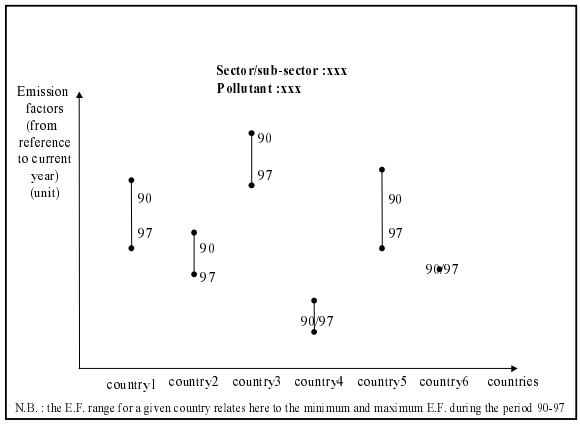

Figure 1. Example graph for an inter-country comparison of emission factors.

Concerning checking of *activity rates*, on the basis of the CRF, common comparable indicators should be defined for the purpose of international comparison (e.g., activity rate per inhabitant, per employee, per unit of GDP, per number of households or per number of vehicles, etc., according to the source sectors). This will enable order-of-magnitude checks as well as checks for outliers that may be caused by input or calculation errors. Comparing with international statistics for national countries, which were in principle independently compiled from the agency that prepares the greenhouse gas inventory, can make a similar check. Countries have to submit *uncertainty estimates* by source or sink categories for each compound given. An international comparison of the figures submitted could be performed on the basis of relative uncertainties (as percentage). For this purpose the following steps could be taken next:

1. Check for each category/compound combination the uncertainty given by the individual country. Those which have an unusually low uncertainty associated with their emissions should be checked individually for consistency of their reporting.
2. Check/calculate total uncertainty of a country for a given compound.
3. Check consistency of given number/uncertainty with verification measurement/uncertainty.

These comparison processes do not always represent verifications of the data themselves, but verification of the reliability and the consistency of data (in trend and across countries). Practically, these comparison processes will enable reviewers to focus on more limited

cases of inconsistencies or doubts for which deeper data verifications will need to be performed. Obviously, the amount of time to be spent on these independent validation and verification activities should be prioritised (see Section 5).

4. OVERVIEW OF OPTIONS AT THE INTERNATIONAL SCALE

UN bodies, governments, individual scientists, scientific research programmes and non-governmental agencies (NGO's) may show interest in scientific peer review or public review of national inventories by analysing and comparing various data sources (official national inventories, other estimates, information available from the UNFCCC secretariat, etc.). In addition, both IPCC WG I and the IPCC Technical Support Unit (TSU) on Greenhouse Gas Inventories will be encouraging these activities from the perspective of improving current knowledge on global budgets, source strengths and representative default emission factors. The following approaches can be identified: (a) international comparisons, (b) comparisons with scientific publications, (c) evaluation of budgets and source strengths, (d) updating IPCC reports. Each of these will be described below in more detail.

Every comparison of emissions can not be interpreted without some quantitative knowledge of the associated uncertainty. As the art of estimating country emissions and their associated uncertainty is at different levels of sophistication in different countries, the Good Practice Guidelines recommend a Tiered Approach aiming at quantified uncertainty estimates [see Chapter 'Quantifying uncertainties in practice' in IPCC (2000)]. Tier 1 is a simplified method for calculating a quantitative *indication of the uncertainty* in the total national emissions by means of classical arithmetic methods of combining uncertainties (assuming standard, Gaussian distributions, independent variables and uncertainties smaller than 60%). Subsequent Tiers use more detailed, data-intensive methods for the uncertainty estimates. However, for performing a Tier 1 calculation of indicator of uncertainty one also needs an estimate of the uncertainty in all underlying activity data and emission factors. It requires at least expert-judgement of the uncertainty as order of magnitude (see Table 1), except for cases where better information is readily available [e.g. selected from a range as described in the Chapter 'Quantifying uncertainties in practice' in IPCC (2000)].

For greenhouse gases one could seek guidance from the qualifications and values already used in UNFCCC submissions, e.g. as reported in UNFCCC (1998). This will provide a means for generating quantitative uncertainty figures for many countries on the short term that can be compared between them. In addition, it will allow reported levels of uncertainty to be evaluated soon in a more comprehensive way in assessments of uncertainties in a broader context. For example in regional or sectoral comparisons and in 'chain calculations' from emissions to climate change, which address uncertainty in all elements of the chain in a harmonised way, e.g. through the use of uncertainty factors. Examples of applications in which uncertainty estimates are an essential element are:

- cross-country comparison for all countries where inventories are available (for checking comparability, inadvertent errors or identifying highly deviating emission factors and/or apparent country-specific circumstances);
- providing uncertainty estimates for world regions (e.g. Annex I countries to the UNFCCC);
- providing (by extrapolation, if required) uncertainty estimates for the world;
- providing insight in the robustness of reported multi-year emission trends;
- comparison with reference inventories developed by other authoritative sources (for checking completeness, consistency, correct source allocation, and for inadvertent errors, which are also aspects of uncertainty within inventories that can only be evaluated using this method) comparison with independent top-down estimates by reverse modelling of atmospheric concentration measurements (for checking for possible biases in country totals or global or regional sectoral totals).

Table 1. Example of a classification of uncertainties

Range(±)	Uncertainty (±%)	Uncertainty Factor*	Confidence	Qualitative description
2-10%	5%	1.05	high	very small
5-20%	10%	1.1	high	small
10-50%	25%	1.25	medium-high	medium
20-100%	50%	1.5	medium-low	large
50-150%	100%	2.	low	very large
100-400%	200%	3.	low	extremely large

* An uncertainty factor UF corresponds with the following range around the emissions level EM: from EM/UF to EM*UF.

4.1. International comparisons

Comparison of national greenhouse gas inventories with international data sources can be a means to independently verify the reported figures, in particular with respect to comparability and possible group bias. In addition to the activities described in Section 3.4, which are done from the perspective of a specific country, we also do a more systematic comparison for a larger group of countries and draw conclusions at another level. Here we can distinguish between comparison with other, but independently compiled, *bottom-up* emission estimates and comparison with emissions based on *top-down* estimates from atmospheric concentration measurements.

4.1.1 Comparisons with emission, emission factor or activity data

Typically, the comparisons are similar to those already introduced in Section 3.4:

- Reference calculation for CO_2 (based on international energy statistics, cf. Section 3.2.4) ;
- Comparisons of emissions with independently compiled estimates (global emission inventories);
- Comparisons of emission factors (outlier detection in implied factors reported to UNFCCC);
- Comparison of emission density indicators (as a quick indirect check/verification);
- Comparisons of activity data (including activity density indicators).

Compared to the Section 3.4 (options at national scale), there is here an important constraint to focus on, which is the necessity for harmonised reported inventory datasets (Lim and Boileau, 1999). The different detailed cross-country comparisons (of sectoral/subsectoral emission factors or activities) assume that such detailed harmonised reported inventories at international level are available. Comparison of national emission inventories with independently compiled authoritative international datasets will assist in checking completeness, consistency, correct source allocation and magnitude of both inventories, national and international. Such global databases currently exist, e.g. on CO_2 from fossil fuel combustion only compiled by International Energy Agency (IEA) and by the Carbon Dioxide Information and Analysis Centre (CDIAC), global total anthropogenic inventories of all greenhouse gases of the Global Emission Inventory Activity (GEIA, a component of IGAC/IGBP) and of the Emission Database for Global Atmospheric Research (EDGAR) compiled by TNO and RIVM in close co-operation with GEIA, or datasets compiled by the World Resources Institute (WRI) (IEA, 1998; Marland et al., 1994; Graedel et al., 1993; Olivier et al., 1999). Emissions of a group of countries (e.g. Annex I, that is OECD countries and Economies in Transition in Central and Eastern Europe) can be compared with regional totals of global inventories that were validated against global, regional and zonal budgets. In particular when emission estimates differ substantially, the emission factors used could be compared in more detail, also with the defaults that the Revised IPCC Guidelines recommend. From these evaluations conclusions can be drawn regarding comparability, applicability of defaults and country-specificity. The same type of comparison as described for emissions can be done with the underlying activity data in order to checking completeness and as an order-of-magnitude check: these can be compared with de facto independently compiled international statistics (e.g. maintained by IEA, UN, FAO, AFEAS). One should, however, not always expect to find exact matches since the activity data used by the inventory compilation team may be taken from different data source or different version of it than the origin of the national data collected by these international organisations. For examples see Schipper et al. (1992).

However, when evaluating the results of these comparisons, it should be remembered that various data sources are not always completely independent of each other. For example, EDGAR starts with IEA energy data to calculate CO_2 emissions from fuel combustion and CDIAC/GEIA start with UN energy data. In addition, even the IEA and UN energy data are not completely independent. In order to avoid duplication of work, the IEA and the United Nations have established a co-operation in data exchange, and receive common questionnaires for some countries. Nevertheless, there are still differences in the data released by the two organisations due, inter alia, to sources of data, methodology, revision in historical series, geographical coverage, etc.

Comparison of emission density indicators, such as emissions per capita, industrial emissions per unit of value added, transport emissions per car, emissions from power generation per kWh of electricity produced etc., provides a quick indirect check and verification of the order of magnitude of the emissions. Of course the correlation between emissions and an independent variable does not necessarily imply cause and effect. However, it is an easy means to flag certain anomalies at country or sector level, if any. More examples for energy indicators can be found in Schipper and Haas (1997) and Bossebeuf *et al.* (1997).

The cross-country comparison of data is relevant if the data are comparable. For the emission factor comparison, that can be possible on the basis of the sectoral background tables of the 'Common Reporting Format' (CRF). The emission factors comparisons can be performed at different aggregation level as far as emission factors have to be reported at different level within the 'Common Reporting Format'. Of course, cross-country comparisons of emission factors can be processed as

far as emission factor units are fixed, or unit conversion ratios are available.

From a practical aspect, different kinds of comparisons could be combined. For example, cross-country emission factor comparison can be combined with historical trend by plotting in a single graph, for the different countries, the reference year data (1990), the more recent year data, and the minimum and maximum value, for each source sector and possible aggregations and according to the fuel types when relevant (see Fig. 1). Another practical example of combined emission factor comparison is the combination with estimated uncertainties when available. In this case, in a single graph, could be plotted for the different countries, the current year emission factor and the related uncertainty range, for a given source sector and according to the fuel types when relevant. This combined comparison including uncertainties is quite important as far as emission factor discrepancies analysis and checks require complementary information on uncertainty, to be more relevant (Figure 2). Thus, from the comparisons of the implied emission factors reported to UNFCCC (as proposed in the 'Common Reporting Format', CRF), if some national emission factors appear to be outliers, further comparison could be made by checking with those used by apparently similar countries. Furthermore comparison with the recommended IPCC Tier I default values and with literature values may be informative in establishing the comparability or the country-specificity of the emission factors used.

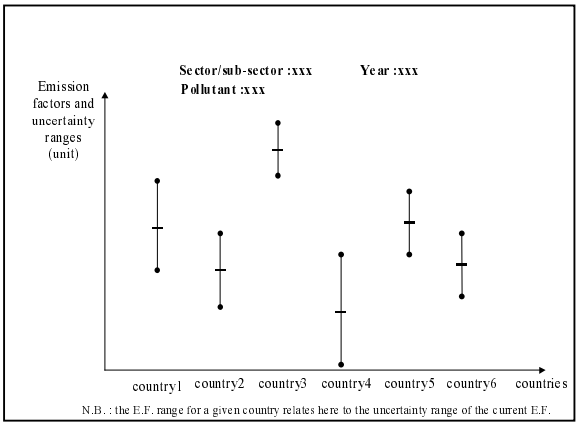

Figure 2. Example graph for an inter-country comparison of emission factor uncertainties.

As for emission factors, the cross-country comparison of activities requires a harmonised reporting format as the 'Common Reporting Format'. But due to country 'volume' effect, apparent activity discrepancies from such crude comparisons, are not really significant. So on the basis of the CRF and the basis of common comparable indicators to be chosen, activity density indicators can be defined, for the purpose of international comparison (e.g., activity rate per inhabitant, per employee, per unit of GDP, per number of households or per number of vehicles, etc., according to the source sectors). The different levels of comparison will also assist in evaluating the estimated uncertainty estimates of national inventories as well as of global emission inventories, especially by checking for any group bias and by the size of the differences at country level that show.

4.1.2. Comparisons with atmospheric measurements at regional and global scale

Evidently, methods for national and international scale do not differ by definition. Comparisons which are useful on the national scale may also be applied internationally (see Section 3 for details). The difference is that at this scale there is increasing possibilities to concentrate on source regions rather than borderline dependent areas. Methods that are otherwise only valid in large countries may safely be applied here. Additional options become available on the international scale:

- *Continental plume*

A strong difference between source and non-source (sink) regions may generally be found between continent and sea. Routine measurements may be performed close to an ocean, at offshore islands, or on ships. In evaluation one may consider the difference between clean background air and the polluted plume, taking advantage of wind sector analysis or trajectory analysis. In European continental plume a number of greenhouse gases, including CFCs, N_2O and CH_4, has been detected at Mace Head, Ireland. The results have been used for subsequent quantification of the European emission source strength (Derwent *et al.*, 1998a,b; Vermeulen *et al.*, 1999). For quantification, an inverse modelling procedure is performed.

- *Satellite observation*

Satellite observations allow retrieving a quasi-continuous concentration profile for all of the globe. The method is still in its infancy, even if specific instruments have already been designed to collect data on climate gases. A sensor currently active is GOME, which has been validated recently to detect total columns of O_3, NO_2, BrO_2, HCHO and OClO (Goede *et al.*, 2000). In spring 2002 SCIAMACHY has been launched, which has a passive spectrometer observing absorption in ultraviolet (UV), visible and near infrared (NIR) spectral ranges. It will be able to yield concentrations of O_3, NO_2, N_2O, CO, CO_2, CH_4 both in the troposphere and stratosphere. Maximum horizontal resolution will be 30 km x 60 km. Thus it seems reasonable to assume that plumes may be detected at different scales.

- *Global dynamic approaches*

Concentration trends of compounds also indicate the result of a discrepancy between sources and sinks. From such trends, conclusions on either of these two

may be drawn, once the other is considered fixed. Such approaches have been taken for methane (Dlugokencky *et al.*, 1994) and SF_6 (Maiss and Brenninkmeijer, 1998).

The obvious advantage of the methods discussed above is that a large share of global emissions is covered, and monitoring is possible on a routine basis. However, it is almost impossible to trace back to individual sources or source sectors, if their emissions do not contain some sort of 'fingerprint'. This may be a specific type of carbon isotope in case of CO_2 and CH_4 emissions from fossil fuels, or typical temporal profile (seasonality or diurnal variation) or zonal variation (e.g. latitudinal distribution), that enables to distinguish them from other sources.

4.1.3. Comparisons of uncertainty estimates of data reported to UNFCCC

The reporting format for uncertainty estimates has been described in IPCC (2000). Countries will submit uncertainty estimates by source or sink categories for each compound given. An international comparison of the figures submitted may be performed on the basis of relative uncertainties (as percentage). The following steps should be taken next:

- Check for each category/compound combination the uncertainty given by the individual country. Those which have an unusual low uncertainty associated with their emissions should be checked individually for consistency of their reporting ;
- Check/calculate total uncertainty of a country for a given compound;
- Check consistency of given number/uncertainty with verification measurement/uncertainty.

4.2. Scientific publications

In the scientific literature there may be publications providing other estimates of national emissions or publications in which the quality of the official national inventory is analysed. Comparison of these different national estimates and the results of those analyses are important elements of a critical check of the quality of the official national inventory, which can be used when comparing or integrating the greenhouse gas emissions of various countries.

4.3. Evaluation of global or regional budgets and source strengths

Confronting summed official inventories with global inventories and with global or regional emission levels established as part of a total budget analysis is a means either to update global budgets or to provide feedback to national inventory developers and IPCC TSU on Inventories on apparent biases. Provided that sufficient information is available on spatial and temporal distribution of the sources, including the natural ones, one may be able to draw conclusions on the likely biases in specific major sources, if these have specific own spatial or temporal characteristics, that helps distinguishing them form others (Heymann, 1996, for CO_2; Janssen *et al.*, 1999, for CH_4; Bouwman and Taylor, 1996, for N_2O). This type of evaluation is the ultimate verification of bottom-up compiled emission estimates since at the global level all emissions are part of a big chain of material flows from sources to sinks.

4.4. Updating IPCC reports

Comparison of emission factors submitted by countries and the methodologies used with defaults recommended by the current *Revised 1996 IPCC Guidelines* and comparison of reported emissions with figures currently used in the scientific literature could also provide important input to revisions of the following parts of IPCC reports:

- Evaluation and updating of defaults methods and emission factors recommended in the *Revised 1996 IPCC Guidelines on Greenhouse Gas Inventories* (IPCC, 1997) (e.g. by comparing sets of nationally applied emission factors with recommended IPCC default values);
- Evaluation of global or regional budgets as currently compiled by IPCC Working Group I (WG I) as discussed and published by the scientific community (IPCC, 2001).

5. WORKING PROCEDURES, PRIORITISATION AND REPORTING FORMAT ON THE NATIONAL LEVEL

5.1 Phases and prioritised national approach

This paper describes many concrete options for checks and verification, some of which are very easy to carry out, others are costly and difficult to implement:

- Immediately available procedures (efficient ones for quick checks; priorities for checking and verifying both large and fast changing components) using national data only;
- Procedures using available international data;
- Procedures to be developed (more elaborated verification, e.g. direct source testing or comparison with atmospheric concentration measurements).

Thus, there is a clear need for guidelines to decide how much time and money should be devoted to checking and verification versus the effort to be put in the basic compilation process (data gathering, calculations, recalculations, uncertainty estimates, reporting).

Evidently, a number of key, basic checks should be routinely incorporated at the appropriate stage in the compilation process. For more guidelines on the pro-

cedure as such, we refer to IPCC (2000) [chapter 'QA/QC of inventory systems']. Here we point out, that the detailed level of checks and verification will be laid out in the QA/QC plan. Those checks will be important on the performance of those sources that apparently contribute substantially to the national emission control programme. In other words, it is recommended that the monitoring of actual emissions as described in the national inventory will be checked for its credibility. Checks involving international data may be applied in more detail for a one-time verification of the inventory; in subsequent years there will be no need for an extensive check of this kind, except for special sector-gas combinations that have at that time particular importance for the country.

For the more elaborated verification activities based on atmospheric concentration measurements, a semi-continuous and internationally co-ordinated research programme 'at the background' is recommended, aiming at verification at national and international scale. Besides tests of aggregation to the global level and comparison with alternatively established budgets, this is the only really independent method for verifying emissions and checking for major systematic biases. Direct source testing should be carried out as part of an overall programme of reducing uncertainties in the total greenhouse gas inventory. Priority setting will be a function of costs, time, and share in total and sector emissions, both in CO_2-eq. and per gas.

5.2. Defining the national procedures on checks and verification

The inventory update programme has different components, each of which will require different types of checks:

- Existing historical inventory in place;
- New additions to the inventory (new years, possibly new sources to be applied also to previous years);
- Finalisation of preliminary data;
- Adjustments to the existing inventory (including recalculation of the historical inventory);
- Conclusions for prioritising future activities (short term and longer term).

In order to minimise resources spent, quality checks and verifications should solely be applied where they have not been used previously, thus, mostly to new data. If the existing historical inventory is left as is, no further checks (or QA/QC programme) are required to confirm this component of the inventory. Thus, apart from a one-time thorough checking of the existing historical inventory, the system would require the following activities to be performed:

1. Comparison of trends and previous reported data (see Section 3.2.1);
2. Checking for methodological changes (see Section 3.2.2);
3. Order-of-magnitude checks (see Section 3.2.3);
4. Reference calculations (see Section 3.2.4);
5. Scientific publications or external review (if available: see Section 3.3.4);
6. Setting priorities for future inventory improvement, including re-evaluation of uncertainties if necessary (based on results of activities above; see Section 5.1).

As a separate item verification activities should be performed, focussing either on large sources or on sources with a large uncertainty:

1. Comparisons of indicators;
2. Comparisons with other independent estimates;
3. Comparison with atmospheric concentration measurements.

Priority setting may be (a) to apply the first two methods for the initial inventory (and to updates for confirmation of trends), and (b) to apply the third method periodically for ground truth verification of absolute emission levels and emission trends.

5.3. Reporting format for national checking and verification activities

Besides annual submission of the annual inventory and associated uncertainty estimate, it is recommended that a separate annual report be published and submitted describing for each of the activities described in Section 5.2:

a) *What* has been checked and verified and why was that selected and how was the QC done;
b) *Feedback* from external reviews: summary of key comments, their origin and actions taken;
c) *Results:* findings and correction of the inventory ;
d) *Recommendations* for inventory improvements.

It is also considered Good Practice that as a separate report a description is available (for the public, external reviews and to other Parties to the UNFCCC) of how the QC activities are structured and embedded in the QA system.

6. INTERNATIONAL ACTIVITIES ON CHECKS AND VERIFICATION

Possible activities executed by or encouraged by UN bodies, governments, scientific community, NGOs, IPCC WG I and the IPCC TSU on National Greenhouse Gas Inventories are:

- Public review of national inventories by comparison with other estimates, scientific publications, in-

formation available from the UNFCCC secretariat, inter-country comparisons;

- Evaluation and updating of defaults methods and emission factors recommended in the Revised IPCC Guidelines on Greenhouse Gas Inventories;
- Evaluation of global or regional budgets by the scientific community and IPCC Working Group I, respectively.

Building up a system for emission verification on the international scale will consist of three stages:

1. Exploring the possibilities of integrating existing networks (e.g. WMO's Global Atmospheric Watch programme; the above-mentioned satellite information) into a global network on international greenhouse gas emission monitoring;
2. Identifying gaps and further needs to a global network; set-up of missing monitoring sites;
3. Development and use of global models to evaluate and interpret measurements.

Work on this subject may be done by individual organisations or as a concerted action, e.g. under the encouragement of policy organisations, by a group of cooperating institutes or coordinated into international research programmes (e.g. of IGBP/IGAC).

Alternatively, an international institution or organisation may be entrusted to handle measurement and evaluation programs concerning emission verification. The mission of such an institution may also be extended towards scenario analyses using models. It may be operated under the auspices of IPCC. A successful example of such a kind of institution is the European Monitoring and Evaluation Programme, EMEP. Like EMEP, a number of monitoring sites should be operated by the individual countries, which then undergo vigorous quality control procedures in order to validate measurement data. This quality test is organised and run by the central institution. The measurement and validation program, as much as the modelling efforts, are continuously being reviewed and improved. It will be the task of this institution to confirm reported emission data or to identify missing spots in knowledge on emissions. This proposed institution would then be responsible for the continuous monitoring and the evaluation of this monitoring. While it will not (or with great difficulty) be possible to identify single outlying sources, an overview on the general agreement of the emission estimations to the scientific understanding of the processes involved will be achieved.

The role of the scientific community is to take advantage of the data collected at this institution, but at the same time use it to challenge their conclusions, in order to further improve possibilities for emission verification. As this topic is fairly new, it may be expected that significant improvements to the techniques described in the previous sections are to be made in the near future, which should be taken up in the routine process as quickly as possible.

7. CONCLUSIONS

Ample opportunity exists for validation (checking) and verifying national inventories. Many options are available at national level, by national teams, ranging from very basic checks to more elaborated verification activities. In addition, specific options are available at the international level, e.g. inter-country comparisons of emission factors and comparisons with independently compiled datasets (global emission inventories and international statistics) or more scientifically oriented ones. An internationally co-ordinated approach of the international options seems the most efficient way for performing the latter activities, both for the basic comparisons as well as for the more fundamental verification activities. Procedural arrangements of checks and verification activities within the quality system for compiling the national inventories, including priority setting and reporting requirements, are key to establish and guarantee the credibility of the national inventories in terms of data quality objectives. These have been summarised by the UNFCCC guidelines for preparing and reporting national greenhouse gas inventories as accuracy, consistency, completeness and comparability.

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7. Uncertainties in Global Emission Inventories

7.1 Introduction

This chapter reviews the means for estimating uncertainty in annual inventories and in emission trends in practice. First, key issues involved in estimating uncertainties in annual *national* emission inventories and in emission trends for individual countries will be discussed, as well as consistency across countries. As the art of estimating country emissions and their associated uncertainties is developed at different levels of sophistication in different countries, the so-called *tiered approach* (a set of methods with an increasing level of detail) is proposed, aiming at reporting of quantified uncertainty estimates in any case. Tier 1 is a simplified method for estimating the uncertainty quantitatively e.g. based on expert judgement, whereas subsequent tiers use more detailed data-intensive methods for the uncertainty estimates. This approach provides a means for generating comparable uncertainty estimates for many countries in the short term. This tiered approach has been adopted by the IPCC in its report '*Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*'. Proposals are in preparation for the Parties to the Climate Convention to include standard uncertainty tables in the current UNFCCC reporting guidelines for the uncertainty in the emission inventory, similar to those presented in the IPCC report.

Next, the uncertainties encountered when compiling *global* emission inventories both annual and in trends will be reviewed, as discussed in the previous chapters. This includes the basic sources of uncertainty at all spatial levels, i.e. global, regional, country and grid, the relationships between sources and countries that need to be considered in view of possible correlations, characteristics of the input data quality and its uncertainty. In addition, examples are provided of how uncertainty can be estimated and managed in practice, and what inventory compilers and inventory users should be aware of when constructing or using a global, or national emission inventory.

7.2 A tiered and standardised approach for estimating and evaluating uncertainty in national emission inventories

Edited version of discussion paper:
Olivier, J.G.J. (1998) *Tiered approach and reporting format for estimating and evaluating uncertainty in emission inventories,* prepared for the IPCC/OECD/IEA Scoping Meeting on Managing Uncertainty in National Greenhouse Gas Inventories, Paris, 13-15 October 1998.

1. Introduction

This paper summarises key issues involved in estimating uncertainties in annual emission inventories and in emission trends for individual countries as well as consistency across countries. Emission inventories for greenhouse gases may contain parts with considerable uncertainty, in particular for non-fossil fuel sources, and may also raise questions on the uncertainty of reported trends in greenhouse gas emissions. However, this should not pose a problem as long as the emission factors used are comparable with those used by other countries - within the uncertainty ranges - or can be justified by special national circumstances. This flags the need for reporting emission factors at an appropriate level, as well as estimating and reporting the uncertainty in factors contributing to sectoral emission estimates.

As the art of estimating country emissions and their associated uncertainty is developed at different levels of sophistication in different countries, a so-called 'tiered approach' aiming at quantified uncertainty estimates may be the most appropriate. Tier 1 is a simplified method for estimating the uncertainty quantitatively e.g. based on expert judgement, whereas subsequent Tiers use more detailed, data-intensive methods for the uncertainty estimates.

Such an approach will provide a means for generating comparable figures for many countries on the short term. In addition, it will allow reported levels of uncertainty to be evaluated soon in a more comprehensive way and assessments of uncertainties in a broader context. For example, it will allow uncertainties to be evaluated in regional or sectoral comparisons and 'chain calculations' from emissions to climate change, which address uncertainty in all elements of the chain in a harmonised way, e.g. through the use of uncertainty factors. In summary, it will facilitate:

- cross-border comparison for all countries where inventories are available (for checking comparability, inadvertent errors or identifying highly deviating emission factors and/or apparent country specific circumstances);
- uncertainty estimates for global regions, e.g. Annex I countries to the *UN Framework Convention on Climate Change* (UNFCCC);
- uncertainty estimates for the world (by extrapolation, if required);
- insight into the robustness of reported long-term emission trends;
- comparison with reference inventories developed by other authoritative sources (for checking completeness, consistency, correct source allocation, and for inadvertent errors, which are also aspects of uncertainty within inventories that can only be evaluated using this method);
- comparison with independent top-down estimates by reverse modelling of atmospheric concentration measurements (for checking for possible biases in country totals or global or regional sectoral totals).

2. UNFCCC/Kyoto requirements

CO_2 emissions from fossil fuel use are, in general, known quite accurately. Therefore, generally speaking, uncertainty in greenhouse gas emissions is only relevant for non-CO_2 gases, which contribute only about 1/4 to 1/3 to total CO_2-eq. emissions of a country. So why are uncertainties then relevant for climate policies in contrast with, for instance, the ECE protocols on the reduction of acidifying compounds? Possibly because in contrast with other emission control policies where a number of technological measures can reduce emissions considerably, mitigation of greenhouse gases appears to be much harder to achieve. For example, this is because almost all measures have only a limited effect and many are needed. If, in addition, the practically feasible reduction potential in CO_2-eq. is the largest for the non-CO_2 gases – since the energy-related CO_2 emission is much harder to control – the robustness of the national policy mix of measures for achieving emission reduction targets is to a large extent dependent on the degree of uncertainty in emissions of sectors that are supposed to contribute substantially to the overall reduction target. However, this picture may change considerably when annual emissions or trends in emissions appear to be much lower (or higher) than the current estimate. A sector contributing, for instance, 10% to the national reduction target may in fact contribute only 5% (or 15%) if its annual emissions appear to be 50% lower (or 50% higher). This effect can be even larger when uncertainties in long-range trends are included (see Fig. 1).

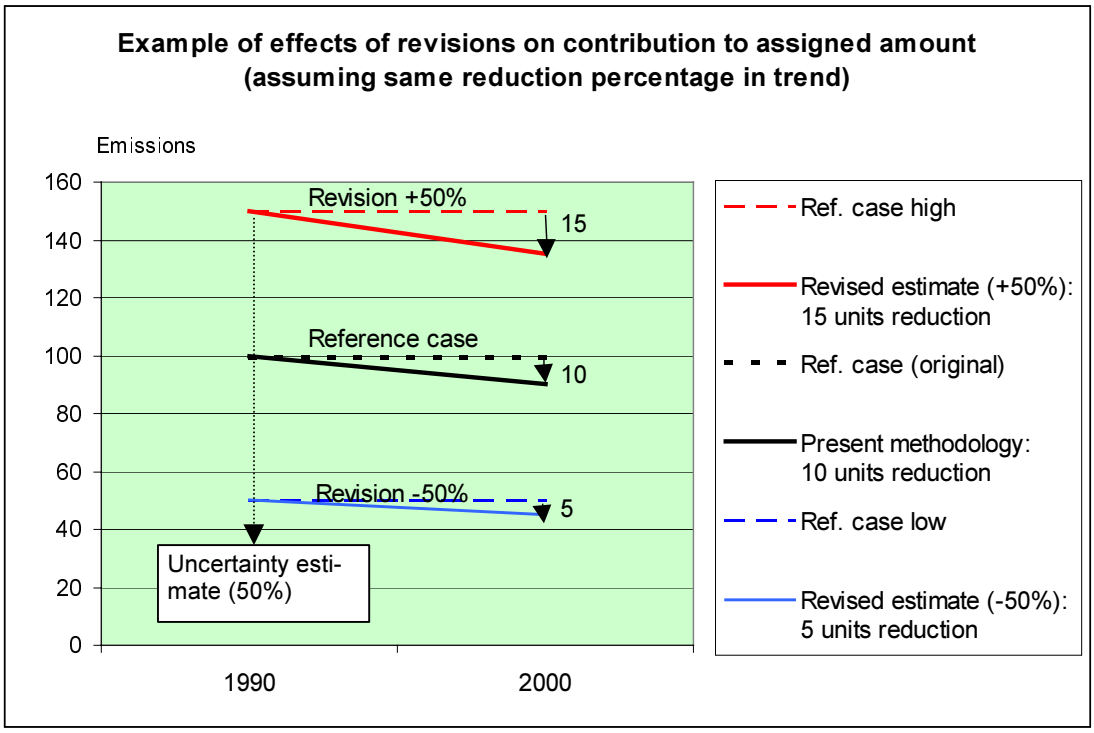

Figure 1. Effects on reduction targets when uncertainties in long-range trends are included.

Thus, from the perspective of the UNFCCC the following aspects would appear to be relevant:

1. ***Uncertainty in annual inventories***
   This uncertainty is relevant if large uncertainties are identified, thus indicating areas of possible significant future changes in emissions due to improvement in methods/data. This also assists in setting priorities for improved monitoring and provides guidance on which parts in the inventory need the best verification or QA procedures. In addition, absolute annual emissions may be relevant for burden sharing within a group of countries of agreed emission reduction objectives (e.g. the Brazilian proposal or the EU burden differentiation, but also for JI and emission trading between countries).
2. ***Uncertainty in emission trends for subsequent years***
   This uncertainty is highly relevant for checking compliance with agreed reduction targets expressed as a percentage of base year emissions (e.g. Kyoto Protocol for 6 (groups of) gases for Annex I countries).
3. ***Uncertainty in geographic details in spatially and temporally resolved annual inventories***
   This uncertainty refers to allocating national emissions to a finer grid and into monthly, weekly or diurnal emission distributions, often required for comparison with back-calculated emissions from atmospheric concentration measurements. This is a truly independent verification procedure for regions or sectors feasible for application at country level when sufficient measurement data are available.

3. Sources and types of uncertainty relevant for greenhouse gases

Emission estimates for specific source categories are usually based on national activity data and emission factors, the latter representing the emission rate per unit of activity concerned. In some cases the emissions depend on other factors as well, for example time-delayed emissions from landfills or refrigerators or climate dependent emissions from natural sources. Subsequently, national total figures may be spatially distributed on a grid (a) using geographical information on the exact location of the sources or (b) using gridded thematic maps as a surrogate for distribution on a grid within a country. When a finer temporal resolution is required, standard procedure is to split up the annual data by using so-called time profiles defined per emission source.

A specific uncertainty that may occur in greenhouse gas inventories prepared according to the *Revised 1996 IPCC Guidelines* (IPCC, 1997) is due to the different emission figures that may result from the use of different tiers that refer to very different methodologies. This may be the case when the *Revised IPCC Guidelines* propose to use a tiered approach dependent

on data availability, but when these tiers refer to very different methodologies. For example including or not time delays in emissions like in methane from landfills. This type of uncertainty can be studied by countries with sufficient data by comparing the results of using the different tiers; even better would be to resolve this discrepancy between tiers. However, we will not address this issue further in this paper.

Uncertainties in national emissions can generally be traced back to the uncertainty in (1) activity data and (2) emission factors. For more detailed inventories in space and time, uncertainty is subsequently added by step (3) distribution of national totals to the grid and (4) distribution over time. We will proceed to discuss variables (1) and (2), which in practice are interrelated:

(1) Activity data

For application of emission factors, a source category is preferably split into subcategories that have distinctly different emission factors, but which can be considered more or less homogeneous with respect to emission factors within these subcategories. When activity data are determined for these subcategories as part of the regular national statistics, standard statistical procedures on data collection should be able to provide numerical estimates of the associated uncertainty unless data are required on sub-activities that are not part of the regular data collection process. If the latter is the case, then on top of the statistical uncertainty in the activity regularly monitored at a higher aggregation level, the uncertainty is further determined by the data quality or estimate of the shares of the sub-activities used for the emission calculation.

(2) Emission factors

Except for a few cases where emission factors are constant in time (e.g. CO_2 per unit of fuel) or continuous measurements of emissions are made, most emission factors will be generalisations of specific emission factors. These specific emission factors are related to either emissions measurements - but usually not covering the full time period during which the source is emitting, in other words not covering all operating conditions - or to specific operating conditions. This means that ultimately the selection of a representative emission factor implies the selection of an emission factor thought by experts to be representative of the overall time-averaged and source-characteristic-averaged emission rate. In doing so, the uncertainty refers to the knowledge on in-homogeneity in source conditions influencing the emission rates as well as the degree of variation of the emission factor in various 'operating' conditions.

The application of emission factors depends both on the level of aggregation for which homogeneous emission factors exist and on the level of aggregation for which activity data are collected on a routine basis. Therefore compromises may, in practice, have to be made since these levels do not always match. In the next sections we will give some examples to clarify this principle.

4. Determination of relevant activity data and emission factors

Coal production statistics are generally available by coal type. However, the methane emission factor is a function of different variables, a key one being the depth of the coal seam that is being excavated. Suppose a number of emission measurements have been taken for various coal types and mining depths, then the question is how to generalise the emission factors for specific measured locations to other coal seams at the same and at other depths. One approach is to distinguish, per coal type, between underground mining and surface mining, since there appears to be a large difference in emission factor values for these two distinct different types of mining. Then one considers coal production per type of mining as the activity data and the emission factor for each type to be used in the emission calculation. Per mining type this is either a weighted average of emission factors for all mining basins (if determined in some way) or the experts judgement of the average emission factor per type. This judgement will take into account the characteristics of the mining influencing the emission rate and the specific circumstances for which the measured emission factors apply. Alternatively, one could consider the total coal production of both surface and underground mining as the activity data, since this is easily available in statistics and derives an average, aggregated emission factor from the weighted average of assumed emission factors for each mining type.

Another similar example concerns emissions from passenger cars. Here activity data may be defined as total fuel consumption by this transport category. Alternatively, one may distinguish between fuel consumption of cars with and without a catalytic converter, or even fuel consumption in different operating modes (cold start, urban, rural and highway driving). Each of these types of cars and driving conditions may have specific emission factors. So if detailed information on fuel consumption at this level is available, the estimation of the applicable fleet-averaged (i.e. for all car types, with a mix of maintenance levels and age classes) emission factors can be done at a lower level. However, this still requires the expert judgement of the average emission factor per type, taking into account the characteristics of the whole fleet in relation to available measured or elsewhere reported emission factors. These examples clearly show that in general:

- Emission factors used in emission estimates depend on the level of detail for which activity data

exist but also on the level of (sub)activities, which have markedly different emission factors.

- Highly aggregated activity data may be readily available from the statistical offices, in contrast with the more detailed subtypes of activity for which data are often more difficult to obtain, their levels less accurately monitored (e.g. by mining type or by type of driving mode) and sometimes also less well-defined.
- Emission factors, whatever their level of aggregation, will in almost all cases represent a selection of values which, according to expert judgement, are representative for the country-wide averaged source strength.
- The definition of activity level, emission factor and aggregated emission factor for a specific source category is not obvious. The best level for estimating total emissions will depend on the levels at which activity data are available and measured or at which reported emission factors are assumed to be applicable. In some cases this may be mine by mine, by individual production plant or by make of car, in other cases more aggregate levels seem to be more sensible to use.
- The long-range trend in emission factors may be dependent on the development of the mix of subactivities, each with a distinct emission factor value as well as on the trend in intrinsic emission factors for a subcategory (e.g. through technological development like the effectiveness of catalytic converters).

From the examples discussed, we can conclude that the aggregation level used for the emission calculation may differ from country to country. This suggests that a common reporting format at meaningful levels of aggregation will be indispensable for evaluating comparability of inventories. It is also clear that statistics of whatever quality are used as activity levels, and subactivity levels when required. Furthermore the selection or adjustment of emission factors is ultimately dependent on the expert judgement of its representativeness of the whole ensemble of sources.

5. Uncertainties related to the selected aggregation levels

Thus the uncertainty in calculating annual national emissions is the accumulated uncertainty in:

1. activity data based on regular (i.e. annual) national statistics,
2. emission factors, be it specific, generalised or aggregated, and, possibly,
3. sub-activity data needed to connect the available emission factors with the available regularly collected activity data.

Guidelines should provide instructions on how the scores for each of these elements should be combined to get the overall uncertainty in the resulting emissions. This aspect will not be discussed here further.

When calculating emissions for a series of years, on top of changing high level activity data, one could assume changes in emission factors, e.g. due to technological developments, and in the mix of subactivities (with distinct different emission factors), used for calculating emissions. Therefore, uncertainty in national emission *trends* is further determined by:

- the derivation of *trends* in emission factors (only if changes in time are assumed, not so much the value itself);
- *changes* in the mix of sub-activities combined to calculate the aggregate emission factor for the higher activity data (only if changes the shares are assumed, not so much the value itself).

For verification of emission *trends* as reported under the UNFCCC, it would be sufficient to know the uncertainty in:

1. high level activity data;
2. assumed changes in emission factors, if any;
3. changes in the shares of sub-activity levels, if any.

6. Reporting format for assessing uncertainty in annual inventories

Keeping in mind the level of reporting required for a useful comparison of aggregated emission factors with other reported values (e.g. to be determined by sectoral exports), the (aggregated) emission factor in one inventory can be compared with the group of other inventories available to check for comparability or large deviations (a possible bias). It seems reasonable that in the latter cases a justification for large deviations is provided unless the value is within two standard deviations from the group average. A similar case would be the observation of large deviations from the emission factors in a reference dataset, outside of their estimated uncertainties. This comparison is only useful when the reference emission factors result in sectoral emission estimates that have been verified for the group of countries or that fit well into a larger global or regional emission budget. In order to analyse the annual emissions reported by countries – using various levels of detail as illustrated above – one would need the following information:

- high level activity data: data (value and uncertainty) and definition of the level of data used;
- emission factors: level of sub-activities for which emission factors are used and the uncertainty in these emission factors;
- the mix of sub-activities used for the calculation, when applicable: data (value and uncertainty).

Obviously, here input will be needed from both statisticians and emission experts involved in the emission calculations.

7. Reporting format for assessing uncertainty in trends

In order to analyse the reported *trends* by countries using various levels of detail, in an ideal situation one would like to have the following information:

1. high level activity data: data (value and uncertainty) and definition of the level of data used;
2. emission factors: level of sub-activities for which emission factors are used and uncertainty found in these emission factors (for one year);
3. justification of assumed changes in emission factors, if any;
4. uncertainty in the mix of sub-activities, when applicable;
5. justification of assumed changes in the shares, if any.

This means that on top of the requirements for estimating uncertainty in *annual* emissions (1, 2 and 4) one needs a justification of assumed changes in parameters that are not always monitored annually and the related uncertainty in these changes. In particular, the input is needed here from emission experts involved in the emission calculations.

8. Tiered approach for assessing uncertainties

As discussed earlier, there is an urgent need for quantitative assessments of uncertainties, but also we see a varying degree of sophistication in compiling national emission inventories. Therefore it is recommended that national teams follow a tiered approach for estimating the uncertainty in the emission estimates, so that at least a first quantitative evaluation for all reporting countries will be possible. A full scientific evaluation in all details at the national level will require time and man power, which may not be available or recommendable. In parallel, countries with more detailed datasets and more capacity may pursue a more detailed scientific assessment of their reported uncertainties.

For annual inventories all tiers should ask for one common format e.g. as specified below, for providing of the following information based on either calculation or expert judgement (or both):

1. ***Activity data for regularly monitored data***
   - specify level of uncertainty
   - specify basis, either calculated or estimated (expert judgement)
2. ***Sub-activity data*** for which specific emission factors were applied at a level meaningful for the purpose of comparison with other datasets (to be determined in reporting instructions)
   - specify (sub)activity level(s) used for the calculation
   - specify level of uncertainty
   - specify basis, either calculated or estimated (expert judgement)
3. ***Emission factors used in the basic calculation***
   - specify (sub)activity level used for the calculation
   - specify level of uncertainty
   - specify basis, either calculated or estimated (expert judgement).

In addition, for estimating *trends* in emissions, Tier I requires uncertainty information on:

4. *Changes in time of the emission factors,* if applicable, e.g. based on expert judgement
5. *Changes in the mix of sub-activities,* if applicable, e.g. based on expert judgement.

In conjunction with the uncertainty in annual emissions, the uncertainty in changes encountered in emission factors and shares of sub-activities determines the robustness of reported emissions trends.

Tier 1

A simple approach, which should be feasible for parties with limited resources, is just to rely on expert judgement for uncertainty estimates in activity data and emission factors. It would also help them in identifying priority areas for improving their inventories. An exception could be made for cases where better information is readily available. This approach requires clearly a classification of uncertainties to be agreed upon by a group of experts beforehand, e.g. as in Table 1.

Table 1. Example of a classification of uncertainties

Range (±)	Uncertainty (±%)	Uncertainty Factor*	Confidence	Qualitative description
2-10%	5%	1.05	high	very small
5-20%	10%	1.1	high	small
10-50%	25%	1.25	medium-high	medium
20-100%	50%	1.5	medium-low	large
50-150%	100%	2.	low	very large
100-400%	200%	3.	low	extremely large

* An uncertainty factor UF corresponds with the following range around the emissions level EM: from EM/UF to EM*UF.

For greenhouse gases, guidance could be sought from the qualifications and values already used in UNFCCC submissions, e.g. as reported in UNFCCC (1998). Perhaps the Data Attribute Rating System (DARS) of US-EPA can be tied in here to derive quantitative uncertainty estimates (Beck, 1997). One also needs to decide which definition on uncertainty to use, e.g. absolute ranges or assumed standard deviation (one standard deviation, corresponding with a 68% confidence interval; two standard deviations, corresponding with a 95% confidence interval). According to the Annex I of the Reporting Instructions in the *Revised IPCC Guidelines*, the definition with two standard deviations should be used.

To reduce the burden for countries, the uncertainty assessment in Tier 1 could be focussed on sectors contributing substantially to either annual emissions or trends in annual emissions or to the emission reduction objective (either per gas or in CO_2-eq., as well as cut-off percentages to be determined by an Expert Group and the UNFCCC bodies).

Tier 2

If a more elaborate emission calculation scheme is used, more detailed activity data collected regularly, and/or more local information on specific emission factors used if available, the uncertainty information as described above can be calculated instead of estimated by whole or partial expert judgement, from the more detailed datasets, using standard statistical methods. However, some expert judgement must always be used to determine whether of not the sample is representative of the true population.

9. Advantages of reporting at fixed sectoral aggregation levels

When reporting instructions would include the provision of sectoral Standard Data Tables (also similar ones for reporting of uncertainties), the aggregated emission factors (and their estimated uncertainty) provided could be compared both with the average group value and with a reference dataset for checking for possible biases in sectoral estimates, like the sectoral Standard Data Tables in the first *IPCC Guidelines for Greenhouse Gas Inventories* (IPCC, 1995). These tables should be modified by sector experts in view of their usefulness for checking comparability. This check can be done by individual countries in subsequent releases of their annual inventory. Furthermore possible inadvertent errors can be removed or large deviations from a group average can be traced and then explained and justified. Alternatively, emission experts may perform analysis on the data submitted by the countries, e.g. as part of a comparability assessment for the UNFCCC or for the IPCC National Greenhouse Gas Inventory Programme, with the aim of improving the guidelines or the default emission factors listed in them.

10. Conclusions

In summary, a tiered approach can be recommended for providing comparable quantitative uncertainty information (including use of expert judgement), based on the observation that many variables used in emission calculations are ultimately based on expert judgement. If in conjunction, Standard Data Tables with meaningful aggregated emission factors are provided for all sectors, these will give added value to the group of emission factors reported by other countries. Provision of these emission factor tables will also allow for self-checks of a country in subsequent releases of its inventory, as well as independent checks of the information provided in the national inventory. Particular important is to check if large deviations of sectors contributing substantially to either annual emissions or trends in annual emissions. To this end, both a range of uncertainty classifications and a useful format for reporting sectoral data should be determined, e.g. by a group of experts. In parallel, countries with sufficient detailed data may pursue and communicate a more elaborate estimate of the uncertainty in emissions. This will provide a sounder basis for improvement of emission factors currently based on expert judgement.

Epilogue

This tiered approach for estimating uncertainties has been adopted by the IPCC in its report '*Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*' (IPCC, 2000). Instead of asking experts to pick an uncertainty estimate from an order-of-magnitude list, such as Table 1, the report provides 'default' uncertainty estimates for national activity data and emission factors for most sources based on expert judgement of the group of experts which participated in the Expert Meetings held in preparation of this report (IPCC, 2000). Also, the Parties to the Climate Convention have adopted guidelines, in which the submission of standard sectoral data tables in so-called *Common Reporting Format* (CRF) files has been introduced as part of the annual National Inventory Report of greenhouse gas emissions (UNFCCC, 1999). These tables include emissions and related activity data and thus also aggregated emission factors ('implied' emission factors as the UNFCCC calls them). These factors are used for checks of comparability with other, similar, countries and for unexpected changes over time. Moreover, at present (May 2002) proposals are in preparation for the Parties to the Climate Convention to include in the current UNFCCC reporting guidelines also standard uncertainty tables for the uncertainty in the emission inventory. Tables similar to those presented in the IPCC *Good Practice Guidance* report, e.g. Tables 6.1 and 6.2, will probably be added to the *Common Reporting Format* data files.

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7.3. Uncertainties in global, regional and national emission inventories

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ABSTRACT: An overview is provided of the uncertainty aspects related to global emission inventories of anthropogenic sources, both *at grid level* (e.g. 1°x1°) as well *global total source strength* used for the construction of global budgets, for a specific year and for trends. The EDGAR 3.2 inventories of greenhouse gases comprise an update of the 1990 emissions of EDGAR version 2.0, more recent emission data for 1995 as well as a trend back in time to 1970. The difference between different versions of an inventory, e.g. EDGAR emissions for 1990, provides an indication of the quality of the most recent statistics available in time as well as the variability during some years as well as of the uncertainty in the methods and emission factors applied. Within the process of constructing both global totals from national estimates and vice versa, often (des)aggregations are made of uncorrelated or of (partly) correlated sources, which have to be taken into account properly.

1 INTRODUCTION

Emission inventories are key to scenario studies and environmental policy development, sometimes called the 'engine house of environmental policies'. A fair estimate of sources, strengths and distribution as well as trends in time, is a prerequisite for selecting cost-effective environmental policy packages and carrying out realistic studies on projections of future emissions. Moreover, atmospheric modellers need the best emission inventories as input into their models, and as modellers are often no experts on emission sources, the expertise of emission experts is key to providing these inventories required for good model performance.

However, the importance of quality aspects of different types of emission inventories is differently valued in policy applications and in scientific applications of emission inventories. This refers for instance to the so-called 'TCCCA' aspects: *transparency* (clarity of source definitions and methods and data used by proper documentation), *consistency* (across years both also across sources of source definitions, methods and data), *completeness* (of sources and years), *comparability* (between countries of methods and emission factors used and of source definitions, also called 'absence of bias') and *accuracy* (availability of an uncertainty estimate of the emission estimates, preferably in quantitative terms) (UNFCCC 1999). Within the policy context, consistency over time and comparability across countries is often considered to be most important, whereas in science completeness and transparency appear to be most important, besides comparability and uncertainty of the emission estimates. Qualification of uncertainty in emission inventories is crucial for scientific analysis to be able to compare and value different estimates and results from different approaches. Still, also for policy purposes knowledge of the uncertainty of emissions per source category can be important to define robust environmental policies. This is in particular the case for large sources that are addressed in these policies which have a high uncertainty but also high potential for improvement of the emission estimates (e.g. by additional measurements or other research). The cost-effectiveness of source-specific emission reduction policies is directly proportional to the change resulting from improved emission estimates. In the case of the relatively new group of non-CO_2 greenhouse gases, which industrialised countries have officially estimated since about 1994/1995, significant improvements of the emission estimates may be expected as a result of various improvement programmes. This will effectively result in revisions of base year emissions as well as in the emission trend.

In this paper we will provide an overview of the uncertainty aspects related to global emission inventories of anthropogenic sources, both *at grid level* (e.g. 1°x1°) as well *global total source strength* as part of the construction of global budgets. However, most global inventories of anthropogenic sources are estimated at country level, using national activity data while using national or regional emission factors. Subsequently, for a given source these national total emissions can (a) be distributed on a grid using appropriate grid maps or point source locations, and (b) be summed to a regional or global total. Therefore a discussion of global uncertainty will automatically include an assessment of uncertainty in national inventories. This paper discusses the uncertainty associated with these emissions and thus of the input data to calculate them. Furthermore its includes an evaluation of the completeness of sources, in particular possible underreporting, the selection of appropriate emission factors and the appropriateness and quality of the grid maps/point

source data used for allocating national emission totals to grid cells. These aspects will be analysed and prioritised for anthropogenic emission sources, both in general and for particular source categories and will be illustrated with results from the EDGAR emission inventory system (Olivier et al. 2001a,b).

2 ESTIMATING AND COMBINING UNCERTAINTIES

In the past, different approaches for evaluating the uncertainty of measurement results have been used without international agreement on how to express the uncertainty. The ISO has developed a '*Guide to the Expression of Uncertainty in Measurement*', often referred to as 'GUM', which provides rules for the expression of measurement uncertainty for use within, amongst others, standardisation and metrology services (ISO, 1995). The GUM is an elaboration of the observation that *a quantitative statement of the uncertainty of a measurement result is required in order to decide if the result is adequate for its intended purpose and to ascertain if it is consistent with other similar results.* The same holds, mutatis mutandis, for the compilation of emission inventories.

According to the GUM, 'standard uncertainty' of a measurement result taken to represent the estimated standard deviation of the result, is defined as the positive square root of the estimated variance of the measurement result. Components of uncertainty may be categorised according to the method used to evaluate them: (A) evaluation by the statistical analysis of series of observations; and (B) evaluation by means of other than the statistical analysis of series of observations. Each component of uncertainty, however evaluated, is represented by an estimated standard deviation, called the *standard uncertainty*. In addition, 'expanded uncertainty' is defined as the standard uncertainty multiplied by a coverage factor, which determines the *confidence interval*. The GUM principles have also been summarised in Taylor and Kuyatt (1994). The *IPCC Greenhouse Gas Inventory Guidelines* (IPCC, 1997) recommend for emissions to use a coverage factor of 2, thus representing a confidence interval of approximately 95%. Uncertainty of a parameter value can be quantitatively expressed in various ways: as absolute or relative uncertainty, as a confidence interval e.g. at 66%, 90%, 95% or 100% level, or as a specific probability distribution function or density function with specific values for their parameters. Examples of density functions are normal, i.e. Gaussian distributions, or triangular, lognormal or uniform distributions.

Uncertainties can be combined using a first-order Taylor series approximation of the formula of variables to be combined, often referred to as the *law of propagation of uncertainty*. However, to simplify the uncertainty calculations it is often assumed that the uncertainties have a *normal distribution* and are uncorrelated, for which a simplified standard uncertainty propagation formula applies for multiplication and addition. Thus, for estimating uncertainty of emissions at global total and at grid level, one needs estimates of the quality of the underlying data, in particular of activity data and emission factors, and also of other parameters used in the calculations if emissions are calculated more complicated than as the product of an activity rate times an emission rate, and subsequently summing over all emission sources. If the data meet the following three conditions:

- size of the uncertainty: < 60%;
- type of uncertainty density function: normal, i.e. Gaussian distribution;
- correlation between data in calculation: none.

then the simplified or standard error propagation rules can be applied. Even if these conditions are not met, one could still use this approach, by the *IPCC Good Practice Guidance* called 'Tier 1' uncertainty assessment, however some caution should be taken in the interpretation of the results (IPCC, 2000).

It should be stressed that the calculated uncertainty ranges are always within the limitations of the method applied for calculating the emissions. If, e.g. for more complex sources, the real emission rate characteristics are much different than modelled, a revision of the methodology could produce a new emission estimate outside of the boundaries of the estimated confidence interval for the uncertainty. Sometimes the limitations of the emission calculation model are included in the uncertainty range, but this may not always be the case. Figure 1 shows the changes in estimated 1990 emissions of the Netherlands over time. It can be concluded that most of the changes in the national total, including most of the methodological changes, are within the presently estimated uncertainty ranges. Most of the changes, however, are the result of emission factor improvements (e.g. from measurements) and error corrections. For individual sources the recalculated emissions are indeed sometimes outside the earlier estimated confidence interval.

3 APPROACHES TO ESTIMATE UNCERTAINTY IN EMISSION CALCULATIONS

The calculation of emissions of most anthropogenic emissions is generally a function of activity data and emission factors per source at country level, which are subsequently either summed across sources and countries to arrive at region or global totals, or spatially distributed over grid cells using specific thematic maps.

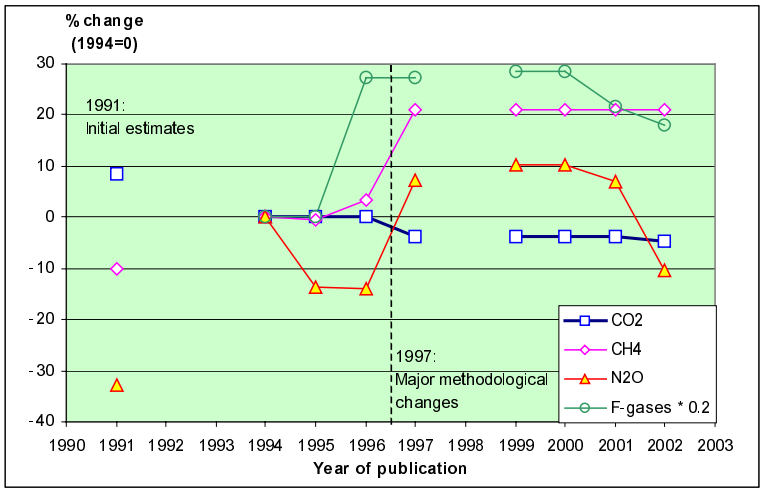

Figure 1. Changes in Netherlands' official total greenhouse gas emissions per gas reported for the base year (1990) since the first official submission in 1994 (1994 = 100). At present, the uncertainty in annual emissions is estimated at ±3% for CO_2, ±25% for CH_4, ± 50% for N_2O and ± 50% for the F-gases (Olivier et al. 2001c).

Uncertainty in input data used to calculate emissions can originate from conceptually different causes:

- intrinsic uncertainty due to variability, i.e. heterogeneity, of the sources
- inexactness due to measurement errors, unclear definitions, etc.;
- unreliability due to methodological limitations such as the use of proxies or limitations in applicability of the model to the practical world;
- questions on applicability or acceptance by peers or stakeholders due to limited transparency of the dataset (definition and accuracy of data) or due to limited validation of the use in emission calculation models;
- ignorance e.g. due to limited understanding of sources, unknown data processing errors, completeness of source categories.

For more details on this subject the reader is referred to specialised research, e.g. as referred to at specialised web sites such as physics.nist.gov/cuu/Uncertainty or www.nusap.net. In this paper we will review at a practical level key sources of uncertainty that need to be addressed when one wishes to make quantitative uncertainty estimates of emissions at higher aggregation levels, e.g. national, regional or global totals of a specific pollutant.

As explained above, the simplified standard error propagation formula for multiplication (emissions = activity * emission factor !) and addition (total emissions = sum of sources and countries !) may be used if one assumes that the uncertainties have a normal distribution. Other conditions for applying these formula are that data are uncorrelated and that the uncertainty is less than 60% (IPCC, 1997). This, however, requires quantitative uncertainty estimates of the underlying data and a good sense of where important correlations are between variables. The latter can often be overcome by making the uncertainty calculation at the proper source or region level.

For many years, emission experts were reluctant to provide quantitative uncertainty estimates. Both in Europe and in North America, qualitative levels, e.g. A to E, were and are used to classify the quality of emissions estimates (EMEP-CORINAIR 1999). Since the *Intergovernmental Panel on Climate Change* introduced quantitative uncertainty estimates in greenhouse gas emission inventories (IPCC 1997, 2000), it is becoming practice to express uncertainty of emissions in 95% confidence intervals, corresponding with a two sigma confidence interval in cases of normal distributions. Unless stated otherwise we will also use this standard in this paper. Until the early 1990's also in global budget assessments it was not common to combine the uncertainties using standard uncertainty propagation formula; rather one was summing the uncertainties of individual sources as if they were 100% confidence ranges, thereby often leading to too large uncertainty ranges for global total emissions (Khalil 1992).

Another characteristic of emission estimates is that often emission factors are assumed to be constant in time, or that they change due to a changing abatement factor with which the fixed uncontrolled factor is multiplied. On the other hand, national statistics are usually collected by periodically sending questionnaires to identified or potential respondents. As a rule, we can therefore say that emission factors are often correlated

in time, whereas statistics for different years are uncorrelated. The uncertainty of the former often is of a technical nature (variability, unreliability, inexactness) whereas national statistics obviously show uncertainty of statistical nature (sampling quality, ignorance) (Rypdal and Winiwarter 2001). The IPCC has developed a method to estimate the uncertainty in emission trends - as opposed to the uncertainty in annual total emissions - using these characteristics of emission factors and activity data for different years (IPCC 2000).

In the following sections we will discuss subsequently the main uncertainty aspects related to (a) activity data; (b) emission factors and associated methodology; (c) gridded by using selected thematic maps. Prior to this, we will look into possible correlations in the input data and how to manage uncertainty assessments in emission inventories. This review of key elements should be taken into account when making uncertainty estimates based on expert judgement. And at the end of the day, expert judgement always plays a role in the final judgement of the representativity of the selected emission factor for the specific source category, specific country or regions and for a specific period. Subsequently, we will discuss the uncertainty estimates made by the EDGAR team as well as observations regarding the variability of annual emissions in time and space that are indications of the uncertainty of a specific emission inventory (Olivier 2001a, b).

4 RELATIONS AND CORRELATIONS BETWEEN DIFFERENT AGGREGATION LEVELS

In this paper we provide an overview of uncertainty aspects related to global emission inventories, both for highly aggregated global total emissions as part of global budgets as well as high resolution gridded global inventories. However, since the construction of these global inventories often relies on national activity data and national or regional emission factors, the uncertainty at the global total level is related to those lower spatial levels. Important aspects to consider are relations or correlations at different *spatial* levels and different *temporal* levels. The latter refers to different time scales: year, seasonality, multi-year trends. Figure 2 schematically shows the different approaches for estimating global total, national total and gridded emissions with the main correlations between sources, countries, grid cells, and years to take into consideration when making uncertainty calculations.

As a rule one can say that most global anthropogenic emission estimates are based on national production and consumption statistics and national or regional emission factors (type A). An exception is the production and consumption of specialised industrial products such as fluorinated compounds like CFCs and HFCs, which are produced by a limited number of companies, for which national statistics are therefore kept confidential. In cases where the environmental impact of those substances is relevant, such as CFCs, HCFCs, methyl bromide, HFCs and SF_6, the major producing companies often release aggregated group totals of global total production and sales, of which the latter are sometimes split into regions or semi-hemispheres (type B). In order to estimate global emissions at grid level of these compounds, first one has to select a distribution variable to allocate fractions of the global total to individual countries. The third approach is estimating emissions directly at grid level, which is common practice for many natural sources, which generally depend on local environmental conditions such as temperature, precipitation and soil characteristics (type C).

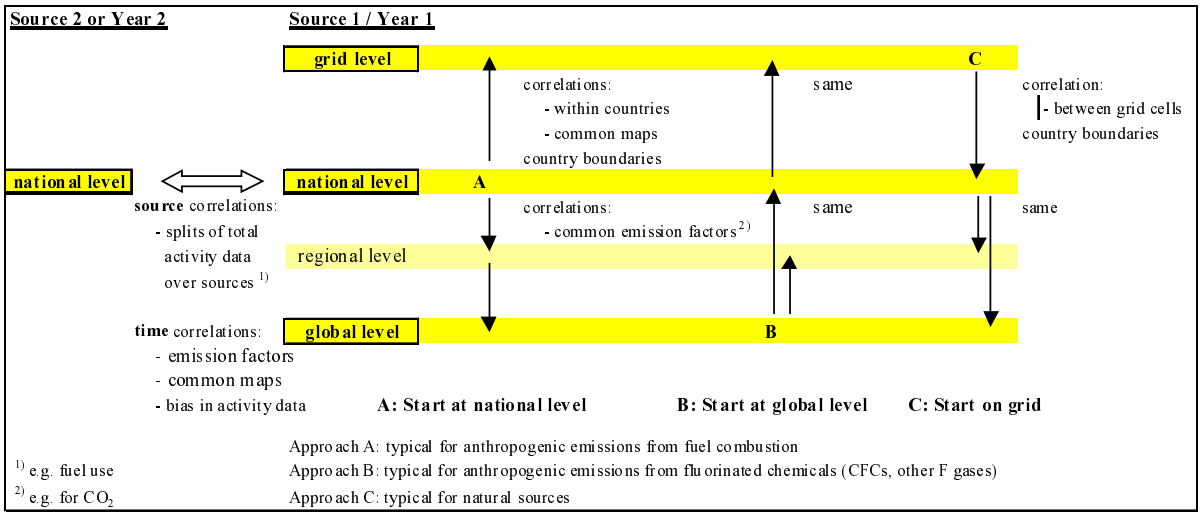

Figure 2. Different approaches for estimating emissions at various spatial levels and the main correlations.

The main correlations that have to be taken into consideration are:

- *between countries*: when using regional or global emission factors;
- *between sources*: 1) when using common emission factors for a group of sources, e.g. the same emission factor for all liquid fuels for all stationary sources or for manure produced by all types of animals; 2) when splitting total activity data over a set of sub-sources, e.g. coal production into surface and underground mining; rice production into rice per ecosystem (rainfed, irrigated, etc.); 3) spatial correlation within countries, e.g. when the same grid map was used for the within country distribution of national total emissions;
- *between years*: 1) often it is assumed that emission factors do not change over time (i.e. between years), e.g. CO_2 factors per fossil fuel type) or that their change can be calculated by multiplying a uncontrolled value by an abatement fraction); 2) also often the same grid maps are used for within country distributions; 3) usually it is assumed that activity data collected through consistent surveys are statistically uncorrelated between years, however if the resulting statistics contain a bias (i.e. a systematic error, for which no correction has been made), then it is likely that the same bias is present in other years as well.

Interestingly, we may conclude that the characteristics and approaches for compiling and assessing uncertainty in global inventories are essentially the same as for and national emission inventories (Rypdal & Winiwarter 2001). In the latter case, national sources can also be a sum of emissions from counties or provinces and at country level gridding of emissions may be done to a higher resolution.

5 UNCERTAINTY MANAGEMENT IN EMISSION INVENTORIES

Estimating uncertainty of calculated emissions is not a goal in itself, but rather it is a means to assess the overall quality of a group of sources. This is done by analysing how uncertainty assumptions for the lowest source level and basic spatial level propagate through the system and add up to the overall uncertainty of a region or a group of sources. Thus, the intended use of emission inventory determines firstly, *which* quality aspects are relevant and, secondly, what the *minimum* quality standard should be.

In emission inventories there are often large differences in order of magnitude of uncertainty in the activity data and emission factors and also between these of different sources. Therefore, initially it is sufficient to *estimate* the order of magnitude of the uncertainty in the input data for the emission calculation. In estimating the basic uncertainties the emphasis should be on the emission factors of rather uncertain but also rather large sources. Moreover, if a source is highly uncertain, e.g. at 100%, but its share in the total is one tenth or less, then the contribution to total uncertainty is very small. Secondly, the inventory should be checked for possible major correlations between sources, locations, years and compounds. Sometimes correlation between input data can be avoided by structuring the uncertainty calculation at the appropriate aggregation level and in the right order. If not, identified correlations will caution against a too strict interpretation of the uncertainty assessment. For example, if emission factors for a source were selected identical within a region, then the uncertainty calculation should be done at regional level, by first summing the national activity data and then multiplying with the emission factor.

Using the same uncertainty data, the *IPCC Good Practice Guidance* (IPCC 2000) also provides a simple Tier 1 method to estimate the uncertainty in *emission trends* (i.e. the per cent point uncertainty in the per cent change in emissions between a start and end year). This method is qualitatively different from other techniques to analyse trends and the uncertainty in it (e.g. by linear or other regression of data points), which may be justified by the nature of emission sources. Often the points are correlated in time through the emission factors (e.g. kept constant or a constant multiplied by a varying abatement factor). If one finds through sensitivity analysis that there are key parts in the inventory that determine to a large extent the total uncertainty, one should prioritise improvements to the emission estimate for that particular source or its uncertainty estimate. In any way, one has identified the key sources for which methodological chances will have a major impact on either total annual emissions or the total trend, in the past as well as in the future.

6 UNCERTAINTY IN INPUT DATA

6.1 *Activity data*

The accuracy of national statistics on activity data used for estimating emissions depends on many and highly variable local and source-specific circumstances. Nevertheless, for a qualitative evaluation they can be classified in the following determining aspects:

- *world region*: often the world can be split into three regions, notably the more industrialised OECD'90 countries, Economies-In-Transition (EIT), i.e.

countries of the former Soviet Union and of Eastern Europe, and the Less Developed Countries (LDC);
- *size of the country*: smaller countries often lack capacity for a fully developed comprehensive statistical system;
- *size of the source:* smaller sources often get less attention in various stages of data collection and data compilation;
- *year*: for a time series comprising decades back in time, data for the last 3-5 years are more likely to be adjusted in subsequent years - and also to a larger extent - than data for older years even when their status has been labelled as 'final'. In addition, data for the oldest years in a time series may also be less accurate if the whole time series has been revised in the course of time for methodological reasons. E.g. when proper data are lacking for making correct adjustments or the revision was only carried out for the most recent part of the time series.

Thus, the origin of the data quality can be characterised by (a) the stage of development of the national statistical systems, (b) psychological and efficiency aspects of focussing attention to the largest sources, and (c) the fact that error corrections are more likely to occur for new data than for older data, since the older data have been reviewed for a much longer period. These elements do apply to statistics compiled by national statistical agencies.

However, the quality of international organisations involved in compiling international statistics based on information provided by individual countries are also influenced by the latter two elements. Such organisations are the International Energy Agency (IEA), the Organisation for Economic Co-operation and Development (OECD), the Statistical Division of the United Nations (UNSD) and the World Bank. Moreover, in their quality assurance programmes the smaller countries are likely to receive less attention, just like as smaller sources get at national level by national agencies. In addition, sometimes data for smaller countries is being estimated by the international organisation by extrapolation or interpolation when countries did not submit the requested data. This also adds to the notion that the uncertainty in the statistics of the smallest countries is larger than the uncertainty for larger countries.

In addition, major source-specific considerations are:
- commercial energy: in general national fossil fuel production data are considered to be more accurate than sectoral consumption data; of the energy consumption statistics, consumption for non-energy purposes (e.g. as chemical feedstock or as lubricant) and for international air and sea transport (bunkers) are considered to be the weakest part of the inventory, also for countries with well developed statistical systems; in addition the sub-split of the 'other sector' into residential, commercial and agricultural consumption is also a very weak element in most cases.
- industrial production: statistics may be kept confidential when there are less then three producing firms in a country; in addition, countries may not always report according to the definition asked for, e.g. only reporting production for external sales, thereby neglecting production at the plant as intermediate product that is processed by the same company. A clear example is nitric acid manufacture, which is predominantly used to produce nitrogen fertilisers, where UN are 40% short of the industry estimate of global total production (Olivier 2001b). At the other hand, overreporting of annual production may occur in cases where internal recycling is not negligible but not subtracted from gross annual production figures.
- another example is the production of fluorinated compounds (CFCs, HFCs, etc.), which is concentrated in a few locations in the world. If the number of firms and the amounts produced are large enough, the group total production and sales by region is generally published through the assistance of an accountant that compiled and checked the confidential individual company data. However, since the production capacity of these F-gases increases of companies in countries not included in the co-operative survey, the uncertainty in the (estimated) global total figures also increases. In general production statistics are more accurate than consumption, import and export figures;
- agricultural data: animal number can be counted in different ways, e.g. at other days of the year, including or excluding the youngest animals; harvested areas may in some cases be underestimated due to underreporting related to tax issues; in crop and wood production statistics different definitions could be used, e.g. regarding the water content and the net-gross ratio;
- waste: in the area of waste statistics many different definitions are used, and detailed studies show that apparent inconsistencies between countries may well be explained by this phenomenon;
- population and Gross Domestic Product (GDP): population, though usually not highly variable, may be counted in several ways, e.g. mid-year or end-of-year, including or excluding refugees, etc.; GDP figures may include inflation or be corrected for them ('fixed prices'); GDP is also often difficult to compare between countries, since one needs a currency exchange rate, which may differ substantially from year to year and within a year. Furthermore, even if one has selected a conversion rate, the purchasing power may not be comparable. GDP may be converted using a Purchasing Power Parity (PPP) conversion factor, but economists will

argue that also this exchange rate has its limitations.

A general observation on international statistics is that they may show substantial differences in some cases to figures taken from the national statistics of certain countries (Schipper et al. 1992). This could be caused by conversions to other source category definitions or to other data selection or processing than has been done for compiling the national statistics. Other sources could be the use of other definitions, units, arithmetic errors, errors in units, power of 1000, etc. Either way, it may be considered as an additional source of uncertainty or as an indication of apparent uncertainty in national statistics for a specific source category.

As mentioned above, the statistics for the EIT countries have been deteriorated after the dissolving of the former USSR. These countries are also an example of possible biases in the national statistics of other countries. In times of fast changes in the economy, the statistical agency may initially not be aware of all new firms in the field, thus not having complete coverage of the questionnaires sent to the relevant groups. Examples are fast growing sectors or fast liberalising areas such as power plants and industry in fast growing economies and electricity and gas trade in the EU. Also there is a question of completeness of sources and source categories: (a) small sources may be overlooked or simply not reported in national statistic; the same holds for new sources, in particular when not very large.

Moreover, statistics may be biased when companies may have a financial incentive for underreporting their activity data (production, arable land area, imports, exports), e.g. when tax rates are related to these activities. Thus the uncertainty range surrounding these data is not symmetrical (statistics are then biased to lower side of the range). An example is the rice cultivation area in China, which is officially recognised as about 25% underestimated. Conversely, also overreporting may occur as explained before (e.g. gross instead of net production of industrial products or of agricultural crops, or including the water content in wood or wood waste).

6.2 *Example of international energy statistics*

These statistics may serve as an example. For OECD countries these are compiled by the *International Energy Agency* (IEA) from questionnaires sent to the member countries, whereas the energy statistics for non-OECD countries are gather by the Energy Division of the UN using similar but not identical questionnaires. Both organisations share their datasets and apply quality control procedures, e.g. checking for irregularities, comparing with other commercial information, and asking for clarifications from the member countries. However, ultimately IEA and UN remain responsible for the datasets that they publish. The quality of the energy statistics varies amongst regions and countries. For energy statistics, data of OECD'90 countries are often considered as having the highest quality, statistics for the Economies in Transition (EIT) as less accurate and the data from the Less Developed Countries (LDC) as having the largest uncertainties (Andres et al. 1996).

Moreover, the uncertainty is generally different for more recent years and for years further back in time. This can be illustrated with the revisions made in the UN energy statistics in the course of time. Revisions may be due to newly acquired data, refined data, or changes in definitions. Some countries may revise datasets regularly, while others never change their statistics. Table 1 shows that, compared with the initial submission in 1983 of 1982 CO_2 emissions, revisions after 5 years show on average an 8% change, whereas in the subsequent 5 years national emissions change markedly less, on average about 0.5%. Further back in time revisions tend to be even smaller. Compared with the 8% difference in 10 years after the initial release, the 2.5% total change in the 1950 data after about 40 years is much smaller (Andres et al. 1996). This is only an indication as to what extent national statistics may change, thereby providing an order of magnitude estimate of the apparent error in the data.

Table 1. Estimated error in national CO_2 emissions calculated with UN energy statistics: % difference of 1983 and 1988 revisions for 1950 and 1982 emissions, relative to 1993 revision.

Year data reported	1950 emissions: average (range)	1950 emissions: # countries	1982 emissions: average (range)	1982 emissions: # countries
1983	-2.5% (-280% to +7.7%)	137	-8.3% (-340% to +88%)	189
1988	-0.5% (-19% to +2%)	136	-0.1% (-79% to +44%)	190

Source: Andres et al. 1996.

Table 2. Comparison of IEA and UN energy statistics: ORNL and EDGAR CO_2 emissions for 1990.

Country group	Mean difference	Standard deviation	Number of countries	Share in global total emissions
Highest emitting countries	0.10	0.11	48	93.7%
Medium emitting countries	0.09	0.26	41	5.2%
Least emitting countries	-0.03	0.61	84	1.2%

Source: Marland et al. 1999.

Table 3. Difference in regional and sectoral CO_2 emissions in 1990 due to updated fuel consumption, fuel production and cement production data in IEA and UN/USGS datasets, respectively (unit: % difference EDGAR 3/EDGAR 2 (corrected for differences in CO_2 emission factors and regional differences in EDGAR 3).

	Global (Pg)	Global total (%)	OECD low	high	EIT low*	high*	LDC low	high
Total fossil fuel + cement	22.4	1%	-9%	-1%	-1%	21%	-18%	6%
Total dom. fuel combustion	18.6	2%	-1%	2%	3%	16%	-9%	7%
Industry	4.5	-1%	-2%	10%	-29%	-2%	-14%	4%
Power generation	6.8	3%	-4%	0%	-9%	23%	-15%	11%
Other sector (residential, etc.)	3.6	6%	-1%	16%	12%	29%	-8%	7%
Road transport	3.3	1%	-3%	3%	0%	1%	-7%	26%
Land non-road transport	0.4	15%	-54%	72%	-28%	25%	-14%	51%
Air transport (all)	0.5	-3%	0%	1%	-12%	-4%	-17%	8%
Other fuel transformation	2.1	29%	-28%	27%	-15%	160%	-60%	180%
Non-energy use	0.1	-55%	-40%	-66%	-70%	-70%	-76%	690%
Fuel used a chemical feedstock	0.2	-65%	-48%	-79%	-17%	-83%	-51%	-83%
Flaring/venting	0.3	6%	-36%	0%	-1%	-1%	-17%	6%
Cement production	0.6	0%	-7%	0%	-1%	-1%	-2%	7%

Source: EDGAR 3.2; EDGAR 2.0. Composition of region grouping: OECD'90: 5 regions; EIT: 2 regions; LDC: 6 regions.
* EIT data cannot be well compared because of the resolving of the former USSR into 15 new countries, for which often 1990 energy statistics had to be estimated.

Another illustration of uncertainty in emissions due to uncertainty in activity data can be found when comparing 1990 CO_2 emissions in EDGAR 2.0 and EDGAR 3.2, when correcting for changes in emission factors (Table 3). It clearly illustrates that activity data, in this case energy statistics, may change substantially in later versions of the same statistics, in particular for non-OECD regions: from –15% to +26% for the largest sources, versus –4% to +16% for OECD regions Also, it shows that generally the largest changes can be found in the smallest sources; an exception is 'other fuel transformation', which is a notorious difficult sector comprising of coke ovens, blast furnaces, oil refineries, gas works, etc., often with inconsistent datasets for inputs and outputs.

Our estimate is that national total CO_2 emissions from OECD'90 countries may have - on average - an accuracy of about 5-10%, EIT about 10-20% (highest value for 1990 and earlier years) and LDC about 10-20% (also see IPCC, 2000). However, also *within* these regions data quality for different countries will vary. For example, within the LDC group one may identify a subgroup of countries with relatively strong statistics databases, e.g. industrialised countries or countries with historical ties to OECD'90 countries, such as American Samoa, Côte d'Ivoire, Falklands (Malvinas), Guam, Hong Kong, India, Israel, Mexico, Oman, Puerto Rico, Singapore, South Africa, South Korea, Taiwan, Tunisia, Virgin Islands (US and UK), Wake Island. In general, data for the smallest countries and sources tend to be the less accurate than those of the larger ones, as is illustrated by comparing differences between CO_2 emissions calculated with energy statistics from the IEA and from the UN (Marland et al. 1999) in Table 2.

6.3 *Emission factors*

Emission factor selection may be based on: (a) comprehensive measurement data; (b) some individual measurements, scaled up to be representative for a whole group of sources, if necessary including corrected for non-representativeness; (c) secondary literature describing factors for other countries; (d) default values provided by emission manuals or guidelines (e.g. *AP-42* in North America, *EMEP-CORINAIR Guidebook* in Europe, or *IPCC Guidelines for National Greenhouse Gas Inventories*). The uncertainty in the selected emission factor will be large in case of limited measurements of a source consisting of a large population of which the emission factor shows a large spread (very variable across individual sources). Also uncertainty in emission factors that are based on literature may be high in cases where the applicability/limitations for usage are not clearly described, i.e. no detailed enough description is given of the sources. For example, combustion technology, variability of emissions rate in time (e.g. start-ups and their frequency), fuel type, maintenance level/practices, cattle feed menu/composition, animal waste management, waste composition. In particular, differences may occur between specially prepared laboratory or official measurement conditions and average conditions in the

real world. An example is the importance of non-stoichiometric conditions for chemical reactions in practical conditions of gas emitting processes. Thus, emission factors may be biased in the following cases:

- not (correctly) corrected for applicability to the source population;
- when emission factors are known to change in time, but to an unknown extent;
- not selected/corrected in the same way as in other, similar, countries (comparability);
- when a standard/limit value is used, instead of lower actual values (e.g. by the reporting firm);
- when a higher than probably actual value is used (e.g. by the reporting firm to have a reduction potential, or by the environmental agency to provoke a response by non-reporting firms in order to better estimate actual emissions).

Often emission factors have been developed for industrialised countries; in those cases it is generally not clear what the effect of lower maintenance levels or other management practices is. Even if emission factor guidebooks provide default emission factors per region, one may wonder what the homogeneity of sources within the region is. If the variability (spread) is known to be large, the key question is whether this value is representative for the source components and source changes of that particular country. On the other hand, the variability between countries may be similar to that within a country, in which case the uncertainty of the emission factor in applying it to a specific country is likely to be of the same order as the uncertainty for the region average value. The comparability of emission factors across countries can be checked by intercomparison of the values of a large set of countries: outliers may be an indication of either estimate errors or of country-specific circumstances. However, one should also be aware of possible correlations between countries (e.g. in case they apply emission factors based on the same literature reference).

6.4 *Grid maps*

The uncertainties in the geographic distribution of emissions are related to the thematic grid maps used to distribute emissions or activities. For estimating uncertainty of emissions by grid cell, three aspects of the allocation maps used to distribute country emissions for certain activities on a grid within countries are important. Firstly, the accuracy of the relative intensities or densities (per country, if used to allocate national emissions). The accuracy of a map could be assessed by comparing different versions of the map - i.e. with different reference years and origin of data. This can be done for example for the population density maps, for which inventories developed by the *Global Emission Inventory Activity* (GEIA) of IGAC/IGBP currently use three maps (Li, Logan/ Harvard and NASA-GISS). These were constructed for different years, with different resolutions of basic data and with a somewhat different methodology to fill in missing sections (rural population). Another aspect is the choice of the theme of the map. This needs to be evaluated, since other themes may result in quite different spatial distributions. The question is how good is a specific map as a proxy for the emission source. Evidently, in the case of a limited number of point sources the availability of a source-specific map is required for an accurate spatial mapping of their emissions. But also here, a change in time not reflected in the point source density distribution, will introduce large uncertainties in these specific grid cells. A third aspect is the way in which border cells are treated in country-to-grid conversions. This refers to both ocean/land cells as well as cells containing areas of more than one country. If treated in a simplified way, e.g. allocating one grid cell to only one country, the effective spatial uncertainty will be two grid cells.

If one common map is used for spatial distribution of all compounds emitted from a specific source, of which the emissions are first calculated at country level, this may give rise to additional uncertainty for specific compounds although at first sight the spatial consistency across compounds seems guaranteed. An example is road transport, of which CO emissions are much higher in urban driving conditions than in rural areas and on highways. For other gases this difference is much less pronounced.

In general it is much more difficult to quantify the uncertainty in the spatial distribution than that in the activity levels or emission factors. One distinction can be made however. The uncertainty in gridded emissions is usually the largest for point sources. The distribution of most other sources has a more stochastic character: usually showing slow changes over time (from year to year) and in the temporal profile (e.g. seasonality). However, in large countries also local effects need to be taken into consideration. For example, given a specific human population map, different climate characteristics will introduce a shift in fuel combustion for space heating towards the colder parts of the country. Likewise will emission factors that are temperature dependent differ according to the temperature gradients across the grid cells, thereby changing the emissions pattern from the underlying spatial pattern of activities (e.g. cattle population). In those cases, using a grid map that distributes the activities properly will not result in the most accurate estimate of the spatial distribution of the associated emissions. However, the uncertainty introduced at grid level emissions by using other maps and different corrections as just discussed can only be assessed by comparing the results using different maps / corrections as different spatial estimates and comparing the emission levels on a grid cell by grid cell basis. Here one could focus on the variability in both the highest and the lowest areas as well as on shifts of the 'hot spot' areas.

Point sources, however, often show a more discrete character in their activities: production is either on or off (during maintenance periods or when closing-down permanently production facilities), or when new production facilities are started. In these cases emissions may increase or decrease substantially in the cause of one year. Since point sources are located in a limited number of grid cells, the overall within country distribution of the source emissions can change largely from year to year or during a specific episode. Often the spatial information used in localising emission sources is not updated frequently, thereby introducing additional uncertainty when using older location information or when using standard gridded emission inventories developed for a representative operational year to a specific time interval. A special effort has to be made to check the actual spatial distribution and local emission rates of point sources in a specific period of time. If this is not done, these additional uncertainties should be taken into account when using the high spatial resolution emission datasets for other time frames than they were developed for.

7 APPLICATION TO GLOBAL EMISSION INVENTORIES

It is been acknowledged, that providing improved uncertainty estimates for the largest or fastest changing sources is an urgent need for models and policy applications, but also that it is hard to achieve on the short term other than through collective expert judgement. The *Global Emission Inventory Activity* (GEIA), part of IGAC/IGBP, aims at assessing uncertainties at country level as well as on grid level for a large group of compounds. Within the EDGAR team of RIVM and TNO per major source category an indication of the uncertainty was given for activity and emission factors separately in terms of small, medium, large and very large. These were stated to correspond with uncertainties of the order of 10%, 50%, 100% and well over 100%, respectively (Olivier et al. 1999). For more detailed assessment of the uncertainty in specific inventories we refer to Olivier et al.(1999) and for conclusions on validation to Olivier et al. (2001b).

To check the usefulness of these order of magnitude uncertainty indications, we translated for methane the qualifications into the percentage ranges mentioned above. Next, we compared our results with the uncertainty estimates used by IPCC Working Group I for the preparation of the *Third Assessment Report* (IPCC 2001). The overall picture showed a rather similar pattern (Fig. 3), which shows that this simple approach and interpretation of uncertainty ranges is still quite useful for application at global levels.

Next, we used these global uncertainty estimates to calculate the total annual and total trend uncertainty in global total methane emissions in 1995 and the 1970-1995 period based on EDGAR 3.2 data (Olivier et al.

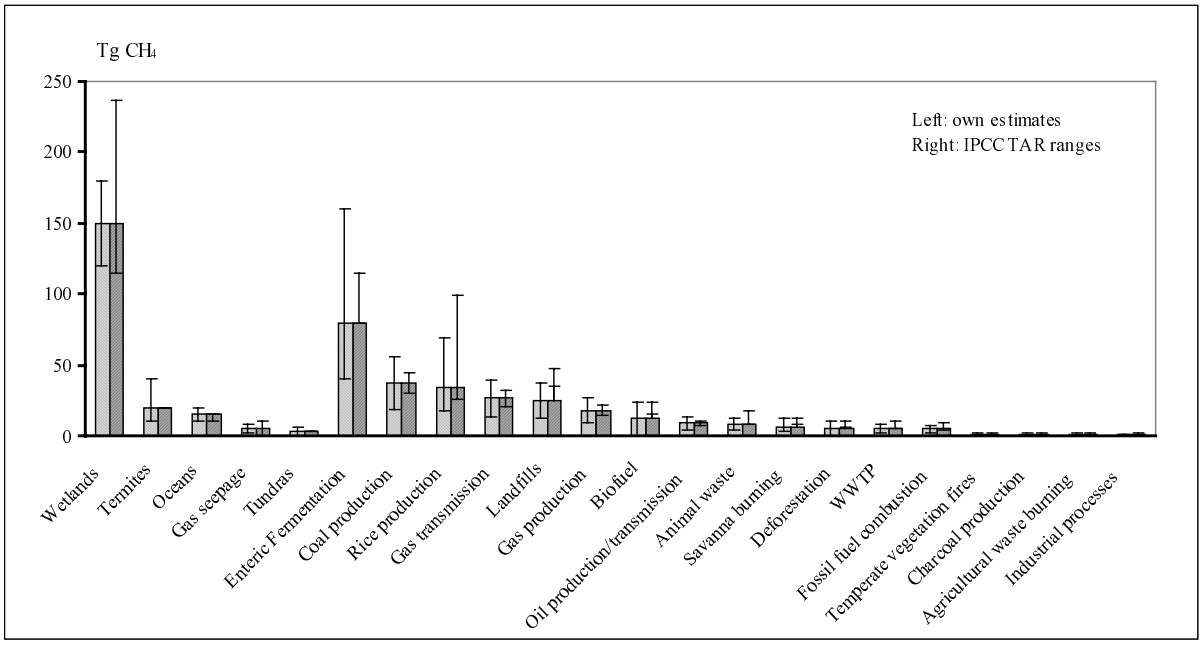

Figure 3. Comparison of uncertainty estimates for major global methane sources (a) using the uncertainty estimates by the EDGAR team and (b) the compilation made for the Third Assessment Report of IPCC Working Group I. In both cases the EDGAR 3.2 source strength estimate is shown.

2001a, b), of which the results are presented in Table 5. Here we applied the default assumptions on activity data being uncorrelated and emission factors being correlated between years (as previously discussed in Sections 4, 5 and 6.2). Subsequently, we analysed the case for three regions, simulating correlations of emission factors within each region as well as region-specific uncertainties in the underlying data. From these calculation we can draw the following conclusions:

- total global annual uncertainty is estimated at 23%, with as largest contributors the categories 4A and 4C, followed by 6A and 1B1 and 1A4; the uncertainty could be reduced to 16% if the uncertainty of emissions from ruminant and from rice cultivation could be reduced by half.
- the increasing trend of 22% globally is surrounded by an uncertainty of ± 18% points.

For the EDGAR database we have, in most cases, estimated average regional emission factors for aggregate source types ('Tier 1' method of IPCC). If we redo the calculation using different uncertainty estimates for the three regions OECD'90, EIT and LDC, the annual uncertainty changes only a little bit: annual uncertainty from 23% to 22%; however the uncertainty in the trend increases from ± 18% points to ± 21% points (Table 4). Thus, in this case refining using a more homogeneous regional assessment does not substantially change the annual uncertainty, but the trend uncertainty is now 3%-points higher. Further investigation may reveal which approach is most appropriate, in view of the correlations identified in this case. Finally, when looking at the update of global total emissions in 1990 in EDGAR 3.2 compared to Version 2.0 (Table 6), we see these figures changed between +7% and -13%, except for N_2O which more than doubled due to a major methodological change (including indirect emissions from agriculture).

Table 4. Uncertainty estimate in global total annual methane emissions and in the 1970-1995 trend (IPCC 'Tier 1' trend).

IPCC category	Source description	1970 (Tg)	1995 (Tg)	AD (unc)	EF (unc)	EM (unc)	Unc 1995 (% nat)	Unc in trend
1A1,2	FF Large combustion	0.3	0.5	10%	50%	51%	0.1%	0.0%
1A3	FF Transport - road	0.4	0.8	10%	50%	51%	0.1%	0.1%
1A4	FF Transport - Non-road	0.0	0.0	10%	50%	51%	0.0%	0.0%
1A4	FF Small combustion	3.0	2.3	5%	50%	50%	0.4%	0.3%
1A1,2	BIO Large combustion	0.0	0.1	100%	50%	112%	0.0%	0.0%
1A3	BIO Transport - road	0.0	0.0	100%	50%	112%	0.0%	0.0%
1A4	BIO Small combustion	8.7	12.8	100%	50%	112%	4.7%	7.3%
1B1	FPR Coal production	32.0	33.4	10%	50%	51%	5.6%	2.2%
1B2	FPR Oil production/handling	7.5	9.2	10%	50%	51%	1.6%	0.5%
1B2	FPR Gas production	5.9	18.2	10%	50%	51%	3.1%	2.5%
1B3	FPR Gas transmission	13.9	26.3	10%	25%	27%	2.3%	1.8%
1B1	FTR Transformation	0.3	0.4	10%	50%	51%	0.1%	0.0%
1B1	BIO Charcoal production	0.6	1.0	100%	50%	112%	0.4%	0.6%
2A	IND Iron and steel industry	0.6	0.8	10%	10%	14%	0.0%	0.0%
2D	IND Organic chemicals	0.0	0.0	10%	10%	14%	0.0%	0.0%
4A	AGR Animals - ruminants	66.9	80.1	10%	50%	51%	13.5%	4.6%
4B	AGR Animal waste	7.0	8.5	25%	50%	56%	1.6%	1.2%
4C	AGR Rice cultivation	51.3	38.7	10%	100%	100%	12.9%	9.9%
4E	AGR Savanna burning	6.3	6.0	100%	50%	112%	2.2%	3.4%
4F	AGR Waste Burning	0.8	0.8	100%	100%	141%	0.4%	0.5%
5A	LUCF Forest fires	6.9	6.5	100%	50%	112%	2.4%	3.7%
6A	WH Landfills	14.8	22.9	50%	50%	71%	5.4%	6.6%
6B	WH WWT	2.9	5.1	100%	50%	112%	1.9%	3.0%
6C	WH Waste incineration	0.2	0.2	100%	50%	112%	0.1%	0.1%
6D	WH Other waste: WW disposal	16.5	27.4	50%	50%	71%	6.4%	8.0%
	Global total	246.8	301.9			23%		18.2%

Source: EDGAR 3.2; uncertainties: Olivier et al. 1999 and recent estimates.

The causes of differences for CO_2 have already been discussed in Section 6.2. This table also shows that global total anthropogenic emissions seem to have changed only very little between 1990 and 1995 as well as between 1995 and 1997. However, inspection of Table 7, which shows the estimated regional changes for 1995-1997, reveals that though global total did not change much, there were major shifts between regions. This clearly illustrates that using an inventory compiled for a specific year in environmental assessments for another year may introduce serious errors.

Table 5. Uncertainty estimate of annual methane emissions and in the 1970-1995 trend: regional approach versus global total.

Region	Emissions 1970	Emissions 1995	Annual uncertainty	Ibid. V2.0 default	Emission increase (Tg)	(%)	Uncertainty in trend	Ibid. V2.0 default
OECD'90	70.7	72.2	± 12%	± 22%	1.5	2%	± 9%	± 18%
EIT	35.0	44.2	± 20%	± 19%	9.2	26%	± 18%	± 17%
LDC	141.2	185.5	± 34%	± 29%	44.3	31%	± 37%	± 29%
Sum (combined)	247	302	± 21%				± 21%	
Global total	247	302	± 23%	± 27%	55	22%	± 18%	± 18%

Source: EDGAR 3.2; uncertainties: Olivier et al.1999 and recent estimates.

Table 6. Comparison of global total anthropogenic emissions in 1990, 1995 and 1997 of selected direct and indirect greenhouse gases.

Compound	1990 EDGAR 2.0	1990 EDGAR 3.2	Difference 3.2-2.0	1995 EDGAR 3.2	Difference 95/90	1997 POET*	Difference 97/95
CO_2	24 900	25 800	4%	27 000	4%	-	-
CH_4	320	302	-6%	302	0%	304	0.8%
N_2O	5.1	11.3	123%	11.5	2%		-
CO	974	846	-13%	861	2%	874	1.6%
NO_x	102	110	7%	111	1%	114	2.7%
NMVOC	149	153	3%	160	4%	-	-
SO_2	178	154	-13%	142	-8%	-	-

Source: EDGAR 2.0 (Olivier et al. 1999); EDGAR 3.2 (Olivier and Berdowski 2001)

* Estimate provided for EU project *Precursors of Ozone and their Effects on the Troposphere* (POET) (Granier, C., 2000).

Table 7. Change in global and regional total emissions in the 1995-1997 period: CH_4, CO and NO_x (% change 1997 relative to 1995).

Region	CH_4	CO	NO_x
(Global total)	(1%)	(2%)	(3%)
Canada	3%	1%	3%
USA	-4%	15%	4%
OECD Europe*	-2%	-8%	-2%
Oceania	0%	3%	5%
Japan	-2%	0%	4%
Eastern Europe*	-3%	-10%	-2%
Former USSR	-9%	-10%	-7%
Latin America	0%	2%	5%
Africa	2%	0%	1%
Middle East	2%	5%	4%
South Asia	4%	1%	9%
East Asia	1%	1%	3%
Southeast Asia	3%	3%	16%

Source: 1995: EDGAR 3.2 in Olivier & Berdowski (2001); 1997/1995 trend: OECD'90 and EIT regions: emissions trends in UNFCCC and EEA databases; LDC: IEA, FAO, UN/USGS statistics. (Visschedijk, A.J.H. 2001. Pers. communication).

8 CONCLUSIONS

The quality of activity data, emission factors and grid maps for emission calculation can be characterised as follows:

- *uncertainty in activity data* is often small, when originating from standard statistics, compared to the uncertainty in the emission factors. However, studies have shown that in some cases international statistics may show substantial differences with figures in national statistics. Sources that are not closely and regularly monitored by national statistical agencies, and therefore showing a substantial uncertainty, are the use of non-commercial fuels, the amounts of other biomass being burned (either at the field, or savannahs, tropical and temperate forests and other wooded lands), and the amounts of waste dumped or burned;
- *uncertainty in emission factors* is quite large when measurement data has to be scaled up to a large population of heterogeneous sources, e.g. in agriculture; it is only small in a few cases where it is directly related to the product composition, e.g. carbon and sulphur content in case of CO_2 and SO_2;
- activity data from national statistics are generally considered as *uncorrelated*, between years and between countries;
- in contrast, in several cases emission factors are to some extent harmonised within regions, thus *correlated,* through the promotion of the use of guidelines, e.g. from EMEP/CORINAIR in Europe, *AP-42* in North America and the *IPCC Guidelines for Greenhouse Gas Inventories*;
- in activity data uncertainties are likely to be *normally distributed* due to the statistical nature of the data - provided that they are complete: if there would have a bias due to known underreporting, a correction should be made, even if it would be a very uncertain estimate;
- the uncertainty *density distribution of emission factors* depends on the basis of the factor and the character of the population of emission sources; they may be skewed, i.e. asymmetrical, if the uncertainty is very high or when the factors may vary up to a specific limit due to environmental standards imposed e.g. maximum sulphur content or emission rate of a specific technology;
- the uncertainty in a selecting a particular *grid map* for estimating the grid distribution of national emissions for a specific source in a specific year is very source-specific and map-specific; it can be very high for industrial point sources, since these have a more discrete nature, i.e. they can shut down or open or expand substantially within a short time, thereby changing the emissions pattern substantially; in contrast, if an appropriate map is used for homogeneous sources with a stochastic character the uncertainty in grid emissions can be relatively low.

Furthermore, we have shown that the characteristics of and the approaches for compiling and assessing uncertainty in global inventories are essentially the same in national emission inventories. Besides these general quality aspects, compilers and users of emission inventories should be aware of the following possible biases:

- *on activity data:* different datasets for any activity may give not identical results due to differences in definitions, units etc.; underreporting may occur (e.g. due to fiscal incentives; in fast changing economic sectors statistical agencies not yet cover all new firms; reporting production for external sales only or for in case of confidentiality, totals for reporting firms only; also overreporting could occur (e.g. wood/wood waste including water content; gross production of agricultural crops or of basic industrial materials);
- *on emission factors:* may not or not correctly corrected for the applicability to the specific source population; may change in time, but to an unknown extent; its selection/correction may differ from other similar countries (comparability); a standard/limit value may be used instead of lower actual values (e.g. by reporting firm); a higher than actual value may be used (e.g. by a firm or by the environmental agency);
- *on gridded emissions:* modellers may ask a higher spatial accuracy of emissions than they can justify in view of other uncertainties associated with their models; emission data can be used for applications outside the validity range; point source activities can change in a 'discrete' way (on/off/expansion) vs. other sources with a more stochastic character; within large countries secondary effects, e.g. climate, may be important aspects to include in the spatial distribution.

Finally, we also showed that emission patterns can change drastically in a five year period, even within two years. Without consideration of these changes, scientific and political conclusions may be easily drawn from analysis using emissions of outdated years as a proxy for present circumstances, as commonly done by modellers and policy makers. This may result in substantial flaws in atmospheric models (e.g. poor model performance) or in the efficiency (i.e. cost effectiveness) of reduction policies. Models like EDGAR can also be used to link official country data with atmospheric models through the conversion to the grid, as part of an interaction between bottom-up and top-down evaluations of annual budgets as well as the trend in them.

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8. Conclusions and Recommendations

This thesis opened with four key research questions:

1. How does a user define the 'quality' of a global (or national) emission inventory?
2. What determines the quality of a global emission inventory?
3. How can inventory quality be achieved in practice and expressed in quantitative terms ('uncertainty')?
4. What is the preferred approach for compiling a global inventory, given the practical limitations and the desired inventory quality?

This chapter summarises the answers to the first three research questions on the basis of information presented in the previous chapters. An answer is also provided to the last question. In addition, conclusions and recommendations are provided for inventory compilers and users, as well as for institutions offering funds for atmospheric research and inventory construction.

8.1 Balancing efforts and inventory quality requirements

Question 1: How is 'inventory quality' defined from the user's perspective?

Since the quality of global emission inventories has several dimensions, each with specific qualitative and quantitative quality aspects, it is the intended use of the inventory that defines which type and quality are relevant and required:

- *Atmospheric modellers* need emission data with a quantitative uncertainty estimate, preferably at all levels, e.g. territorial annual total, precision of temporal variation, precision of spatial distribution and trends. Of course a high level of accuracy is preferred, since it will better test their modelling of air transport and atmospheric chemistry, and assist in budget analysis at global or regional levels. In any case a confidence interval of the emission estimates is required for such analyses, in particular at the levels where comparisons are made, e.g. global total, hemispheric totals, latitudinal distribution, seasonal distribution, each of these examples per major source category. Sectoral details are important since sources often show different 'fingerprints' in their spatial and temporal distributions and in trends over longer time periods. The uncertainty range needs to reflect the uncertainty in the estimated emissions for the specific years applied by the user.

  If the inventory is used by scientists in so-called *episodic* model runs, determined by the period for which atmospheric concentration measurements and model winds etc. are available, inventories are required for a *particular* time period. If the inventory is constructed for another year/period, it is not enough to state that the inventory presents 'representative' spatially distributed and seasonal emissions for the required period. Rather, the additional uncertainty of using the inventory as estimate for the another year/period than for which it was developed should be estimated.

- *Policy makers* need to trust national and sectoral totals sufficiently so that the public and enterprises are willing to take action, convinced of the reliability in the monitoring of present emissions and of progress towards emission targets agreed upon. This does not mean that the accuracy must be high, but that given the knowledge base, unbiased estimates should be made. Preferably it should also be unlikely that emissions will be adjusted substantially in the near future in response to research efforts (planned or unplanned). In other words, surprises should not be likely and the emission figures used, in particular the trends over time, should not be heavily queried by policy makers, society or the scientific community. Uncertainty assessments may be warranted for deciding on the priority for improvements in the monitoring, in particular, in trend monitoring. These assessments will also reveal in which parts of the inventory surprises could occur and what the maximum change in emission estimates, if any, could be.

In both scientific and policy-oriented cases a reasonable *accuracy* of *annual* global or national and sectoral totals is demanded. However, natural emissions should be provided for most modellers as well. For the majority of policy applications this is not a requirement (except for verification purposes). Moreover, the inventories should be complete in the sense that all significant sources are included. For policy and public use reasonably accurate *trend* estimates are often also needed, in particular, at sectoral level. Atmospheric modellers usually request a specific minimum spatial resolution and a certain spatial coverage (continental, if not global). However, the accuracy required at this resolution is often not defined or not well-defined. Moreover, depending on the type of model application, the inventory needs:

(a) to resemble emissions either for a specific year and specific temporal profile within the year (e.g. seasonality) – so-called episodic emissions; or

(b) to represent 'average' emissions for a certain period in time, often with representative (= 'period average') source strengths, spatial distributions and temporal variation (when the modeller is combining atmospheric measurements of several years and historical meteorological datasets); or

(c) to provide emission trends at sectoral level for several consecutive years, with sectoral emissions possibly including spatial and temporal distributions for each year. In the latter case trend estimates are explicitly requested. However, also for the other two cases it is important to know the structural trends in emissions or interannual variability to be able to make a proper estimate of the inventory uncertainty for these applications. A clear example is large-scale biomass burning, which may change substantially from year to year, depending on weather conditions. Other anthropogenic activities may, however, also change substantially globally or in specific countries in certain years (e.g. during and after the Gulf War or during short economic recessions).

Another scientific requirement is the use of a specific compound for calibration purposes of the transport component in the models, where one would like to know both the annual source strength as well as the spatial distribution of the emissions as accurately as possible. Quite another modelling application is the use of an emission inventory for a recent year as the base year for the construction of emission scenarios for future time periods. Here, a good sectoral and regional allocation of the annual emission estimates for the selected year is important. In addition, it helps when these inventories are available for a historical period, for example, for testing and calibrating the scenario models.

In addition, there are the other 'TCCCA' criteria: *transparency, consistency, completeness* and *comparability*. Obviously these are important elements for policy applications in the field of climate change, as they are included in the UNFCCC Guidelines for national greenhouse gas inventories (see Section 2.2). However, in scientific applications these aspects are also important for inventory construction, in particular, the transparency and comparability of global emission inventories (i.e. unbiased estimates). Furthermore, spatial and temporal consistency across gases is required for model applications in which local or large-scale atmospheric chemistry is important. Clear documentation of data sources, methods used, uncertainty estimates and verification by comparison with other studies is essential to check for absence of a large bias in the estimates.

In conclusion, quality requirements differ among users. They may differ substantially, not only between scientific and policy-related applications, but also within the these two groups. An important distinction between policy-related and scientific applications is often found in the different source detail that these two application types can demand or cope with, respectively. These applications require different levels of detail and specification of such items as the source breakdown, and spatial and temporal resolution. As a consequence, and depending on the specific application, users will also have different priorities with respect to the various quality aspects of the global estimates of the various levels of aggregation as discussed in Section 7.3.

Question 2: What determines the quality of a global emission inventory?

In the previous chapters different methods and approaches for constructing a global emission inventory were analysed. Several examples have been presented here of direct estimation of emissions using activity data at national level, emission factors at different source levels, spatial levels, and for different years and selected grid maps to compile gridded global emission inventories. The practicalities that determine the uncertainty and other quality aspects of global emission inventories have been shown. These are:

- selected *level of detail* of sources in the inventory;
- activity data *availability* and data *limitations* (both annual data as well as temporal variation);
- *additional assumptions* necessary for a complete global coverage at national level and a complete time series of activity data;
- the question on how *representative* selected emission factors are for the sources to which are applied;
- *applicability* of grid maps developed for a particular activity to a specific source.

These elements determine to a large extent the intrinsic quality of the inventory, i.e. the quantitative uncertainty in the emission figures as an estimate of the real emissions, in other words the *accuracy* or *uncertainty* of the emissions. In Section 7.3 we reviewed how the quality of these elements can be analysed in terms of uncertainty in inventory components, as well as the relationships that need to be considered for estimating the uncertainty at higher aggregation levels (e.g. emission total per source category or per region).

We also showed that different inventory approaches have different characteristics in terms of the importance of quality aspects such as the 'TCCCA' criteria:

- *transparency* (clarity of source definitions and methods and data used in proper documentation),
- *consistency* (across the years but also across sources, of source definitions, methods and data),

Table 1. Characteristics of bottom-up methods for global inventories according to the TCCCA criteria

Approach	Transparency	Consistency [1]	Completeness	Comparability	Accuracy
Official national inventory	[5]	[2]	- .	[2]	+
Direct estimation by national statistics	+	+[1]	+ [3]	+	- [4]
Hybrid approach [9]	[5]	-	+ .	-	+
Direct estimation by global statistics	+	+[1]	+ [3] [6]	+	- [7]
Grid-based, complex models	+	+	[8]	+	-

[1] Across countries.
[2] Internal consistency and comparability (across years and sources) can be high.
[3] In terms of global coverage.
[4] Except when the emission factors show little variability between countries.
[5] Transparency is limited by limited information provided on the quality of the official national inventories used in the compilation.
[6] If the global total includes all countries.
[7] May be high at global level, if the variability of emission factors across countries/regions is small.
[8] Depends on the model and spatial coverage.
[9] A combination of the direct estimating method as global default and replacing parts by official national inventories.

- *completeness* (of sources and years),
- *comparability* (between countries of methods and emission factors used, and of source definitions, also called 'absence of bias') and, of course,
- *accuracy* (availability of an uncertainty estimate of the emission estimates).

Depending on the type of user, each of these aspects is considered to be more important or less important. As discussed in Section 2.2 the various bottom-up methods tend to focus more or to focus less on each of these criteria, as illustrated in Table 1.

Looking at each of the criteria separately, the *pros* and *cons* of the different methods can be summarised as follows. *Transparency* is a characteristic of most of the methods. An exception is the hybrid approach, where documentation of the data and methods is hampered by the various independently compiled national inventories included, usually without a full description in the main documentation of the global inventory. Although, in practice, this may also apply to single official national inventories, it is not a general characteristic of them. *Consistency* in using the same methods for the same sources across countries is generally not met when concatenating different official national inventories. The same applies, therefore, to the hybrid approach. However, the internal consistency (i.e. across years and source definitions) of official national inventories can be high. *Completeness* in terms of global coverage of the source or the sources is generally attained through the two direct estimation methods and the hybrid method. For official national inventories, however, there is no guarantee that all sources will be covered: e.g. international transportation or natural sources may be excluded. Likewise, the coverage of grid-based models depends on the model and the spatial coverage for which the model has been developed. On *comparability,* all methods but two have a positive score. Obviously the comparability of national inventories is not guaranteed, unless there are strict conditions for the inventory construction posed by international treaties such as the *Climate Convention*. The same, therefore, applies to the hybrid approach. The *accuracy* of global inventories at country level is expected to be highest in collections of official national inventories, where the best use has been made of the knowledge of local source characteristics. Of course the same applies, but to a lesser extent, to the hybrid approach. The direct approaches will not provide very accurate emission estimates at country level except, for example, in cases where emission factors show little variability across countries or when country-specific emission factors have been applied. Grid-based inventories also usually show large uncertainties in emissions at country level due to the inherent large uncertainties and the variability in the input data for the source. However, the direct estimation methods may be able to provide reasonably accurate emission estimates at *regional* and *global* levels, since the uncertainty in the totals may be reduced through the aggregation of sources and countries.

Question 3: How can inventory quality be achieved in practice and expressed quantitatively in terms of uncertainty?

In Chapters 3 to 5 we presented several examples of the compilation of global emission inventories for a specific year and time period, each with their own rationale for their construction. As discussed in Chapter 2, the accuracy of a global emission inventory can be estimated at various levels of detail of the inventory:
(a) sources (total or per source category);
(b) spatially (global total, regional or country total, or per individual grid cell); and

(c) temporal (annual total, trend uncertainty for multi-year period, or for shorter time periods, e.g. seasonality).

The accuracy of the inventories as a whole has been addressed by estimating the order of magnitude of the uncertainty in the underlying data, notably of statistics, emission factors and grid maps. These estimates were partly based on other estimates found in the literature and partly on one's own expert judgement of the inventory compilation team. However, the uncertainty in the resulting global emissions per source was often addressed semi-quantitatively by referring to different levels of uncertainty associated with different spatial aggregation levels: smallest at global/regional level, larger at national level and often very large at grid cell level. Comparison with other estimates, as part of the validation of the inventory, also provides an indication of the apparent uncertainty in the datasets, i.e. assuming that the datasets all have a similar quality. In Sections 4.2 and 7.3 we also showed that these order-of-magnitude estimates of uncertainties produce results that are similar to confidence intervals compiled by other experts. Moreover, we showed that the IPCC approach for estimating the uncertainty of emission trends in national emission inventories can also be applied to global inventories, when taking into account possible correlations between sources and years – similar to assessments at national level – and between world regions.

The uncertainties in a global emission inventory originate from many sources, as was clearly shown in Section 7.3. Although there are many statistical and non-statistical uncertainty elements in the activity data, in most cases the basic statistics can be considered as fairly accurate when compared to the quality of the emission factors and grid maps applied. Here the largest uncertainties can be found in the quality estimate for extended or adjusted time series, and in the estimate of data quality for non-OECD countries. The selection of emission factors for a specific source and the evaluation of the representativity in terms of an uncertainty estimate for application to the sources involve careful expert judgement of the origin of the emission factor and the characteristics of the 'population of sources' such as heterogeneity. Therefore it cannot be excluded that both the emission estimate and the uncertainty estimate include a bias. However, defining the confidence interval for the resulting emissions, albeit estimated, is required to be able to compare an emission estimate with other data. Basic scientific methods are available to do this as objectively and accurately as possible. These include screening of the literature on emission factors, comparisons between these factors and an analysis of the causes leading to differences.

However, since data selection and estimation of the uncertainty in the resulting emission estimates ultimately involves at least some expert judgement, there may be some bias included. Therefore it is important to validate and verify the resulting inventory. We showed that, in principle, available options were *plentiful*. However, the *really independent* verification options have their limitations too, both in terms of costs (direct source testing) and accuracy (inverse modelling). This suggests that integration of several methods and approaches, including global or regional budget analysis, may be the way to achieving maximum confidence in the emission inventories used.

Question 4: What is the preferred approach for compilation of a global emission inventory?

The construction of an emission inventory consists of five phases: first, selecting the coverage (sources, area, time period) and the approach and method that fits best to the user requirements; second, selecting the data sources; third, the actual compilation of the inventory, including extensions, adjustments or modifications when required to achieve the completeness, consistency and accuracy aimed at; fourth, quality assessment by verification and validation of the results; and finally, documenting the inventory to include the results of the quality assessment.

To meet the requirements of different types of users, with their various questions on quality and different priorities, the inventory compiler has to make choices in priority-setting as well. This is because the bottom-up methods show characteristic differences in addressing various quality aspects (Table 1). Moreover, since both human resources, data and time are limited, priority-setting is needed to achieve the best result possible, i.e. fitting best to the needs. This involves an evaluation of quality elements considered to be the most important, prior to selection of the method and approach for the inventory construction. Next, data sources for activity data, emission factors and grid maps need to be selected. Often the datasets available do not exactly meet the requirements and adjustments, extensions, further breakdowns or other modifications that are considered necessary to obtain the required completeness and breakdown of countries, sources and time period. Since these additional modifications of the datasets are often labour-intensive, there is a trade-off between improving completeness and improving the global or regional total emission estimate. In several cases, however, modifications can not be avoided due to incomplete time series in statistical datasets for key countries and sources, or due to structural differences or changes here that determine the country-specific or region-specific emission factors. The preceding choices illustrate that there is no 'best' approach for compiling a global emission inventory. Each of the five bottom-up methods presented has its strong and weak elements (see Table 1). Rather, inventory compilers should in advance analyse which quality aspects should be fo-

cussed on and which sources are most important. Combining this analysis with the availability of activity data and emission factors at appropriate levels for these key sources and the pre-estimated fraction of non-key sources, provides the basis for priority-setting for the actual construction of the inventory. Needless to say, sufficient time should be reserved for laying finishing touch: validation and verification of the inventory and properly documenting it including an assessment of the uncertainty in the data. Without proper documentation it will be very difficult – if not impossible – to evaluate a few years hence what the usefulness and quality for a specific application is.

In Section 7.3 several aspects were presented, that compilers and users of global emission inventories should be aware of, which may introduce an (unknown) bias into the inventory or in the associated uncertainty estimates. This includes the basic sources of uncertainty, the relationship between sources and countries that need to be considered in view of possible correlations and characteristics of the input data quality and its uncertainty. Several examples have been provided of how uncertainty can be estimated and managed in practice and what inventory compilers and inventory users should be aware of when constructing or using a global, or national, emission inventory.

Since all bottom-up inventories compilation methods essentially rely on the same basic data (activity data and measured or reported emission factors), independent verification of the resulting emission estimates is essential to check the absence of a bias. The only means of independently verifying national or global emissions inventories are direct source measurements, comparison with global budgets based on the synthesis of all knowledge on global material flows, or comparison with top-down estimates from inverse modelling. Direct source measurements may be cost-effective in some cases of large point sources but are, in general, not technically or economically feasible for most sources. Comparison with global budgets is simple and should be recommended as a mandatory check but can only be used for complete global inventories, i.e. for all countries and sources. However, such a comparison only serves as a rather crude check for large biases. This leaves us with the third option of comparison with top-down estimates. At present, there are several strong limitations on the use of inverse modelling for verification of emission inventories at national or regional levels. It is even harder to address emissions by sector using this approach. Even distinguishing the anthropogenic part may be difficult to accomplish without additional *a priori* information such as on seasonal variation of sources and their geographical distribution. For the longer-lived trace gases the signature of emissions sources in the concentration fields are fairly small. Also, limited atmospheric concentration measurements, dependency on model parameters and the potential high variability of actual emissions in a specific time period of some anthropogenic sources in case of episodic model calculations limits the current applicability of this verification option. Benchmark studies, in which the inverse modelling results of a set of models are compared, may provide a means to assess the uncertainty generated by the model structures.

From the discussions above we may conclude that a combination of independent bottom-up emission estimates, based on consistent methodology, and atmospheric measurements and atmospheric dispersion models, are preferred tools to ascertain that:

- bottom-up emission inventories reflect the scientifically established atmospheric budget of emissions of greenhouse gases on global, regional and national scales; and
- the official national emission inventories, for example as reported in *National Communications* and *National Inventory Reports* of greenhouse gas emissions show the scientific credibility required to ensure (a) public involvement with the policy goals at the domestic, national level, and (b) acceptance of reported emission trends by other countries committed to these international agreements.

In conclusion, we recall that there is no 'best' approach for compiling a global emission inventory. However, irrespective of the approach and method used for the construction of the global inventory, documentation of the inventory is a key to enable – after the completion of the inventory – the evaluation of the appropriateness for the intended applications. Inventory compilers can only try to anticipate for which type of applications the inventory will be used, focus the inventory construction on those aspects and those sources that are most important, and document the inventory with the possible applications and users in mind. Since inventory compilers are not clairvoyant, providing global emission inventories to the scientific and policy communities is very helpful for compilers, giving them a clear picture of the incredibly wide range of applications of such datasets through the feedback from the users. Moreover, it is an excellent manner to verify the quality of the dataset and to obtain stimuli for continuing research.

8.2 Recommendations

For inventory compilers

Inventory compilers should in advance analyse: (a) which aspects they should focus on in view of the user requirements and (b) which sources are the most important. In combination with availability of activity data and emission factors at appropriate levels for these key sources and the pre-estimated fraction of

non-key sources, this analysis provides a sound basis for priority-setting for the actual compilation of the inventory. In addition, sufficient time should be reserved for validating and verifying, and properly documenting the inventory. This should include an assessment of the uncertainty in the data, whenever possible with literature references for the key uncertainties. Without proper documentation it will be very difficult – if not impossible – to evaluate a few years hence what the usefulness and quality of the inventory for another application is. Evaluation of quality elements considered to be most important will also help in selecting the method and approach in the inventory construction. The following characterisation of the quality of activity data, emission factors and grid maps used for emission calculation can be used as guidance to estimate the uncertainty in the inventory components:

- Uncertainty in *activity data* is often small, when taken from standard statistics, compared to the uncertainty in the emission factors.
- Uncertainty in *emission factors* is fairly large when measurement data have to be scaled-up to a large population of heterogeneous sources, e.g. in agriculture. Uncertainty is only small in a few cases where it is directly related to the product composition, e.g. CO_2 and SO_2.
- The uncertainty in a particular *grid map* can be very high for industrial point sources, whereas for homogeneous sources with a stochastic character, the uncertainty in grid emissions can be relatively low.

For estimating the uncertainty in the resulting emissions, either annual or trend, the following assumptions may be used as default:

- for *correlations*: the activity data from national statistics are generally considered uncorrelated for years and countries; in contrast, in several cases, emission factors are to some extent harmonised within regions, thus correlated, through the recommended use of guidelines
- *uncertainty* in activity data is likely to be normally distributed due to the statistical nature of the data - provided that they are complete. If there were a bias due to known underreporting, a correction should be made, even if it were to be a very uncertain estimate. For emission factors this will depend on the origin of the factor and the character of the population of emission sources. However, as a default, one could start with a normal distribution.

Besides these general quality aspects, compilers and users of emission inventories should be aware of the following possible biases:

- *on activity data:* different datasets for any activity may not give identical results due to differences in definitions, units etc. Underreporting may occur (e.g. in rapidly changing economic sectors statistical agencies do not yet cover all new firms); overreporting could also occur (e.g. due to reporting gross instead of net production).
- *on emission factors:* may not – or may not accurately – be corrected for the specific source population or may change in time. Selection/correction of emission factors may be done differently by similar countries and reporting firms or the environmental agency may have incentives to use either higher or lower values than the actual ones.
- *on gridded emissions:* modellers often ask a higher spatial accuracy of the emissions than they can usually justify in view of the other uncertainties associated with their models. Point source activities can change in a 'discrete' way (on/off/expansion) as opposed to other sources with a more stochastic character. In large countries secondary effects like climate may be important to include in the spatial distribution.

Since emission data can also be used for applications outside the validity range, providing proper documentation along with the inventory may help to avoid incorrect usage of the dataset, including application to other years in cases where compilers know that emission patterns have changed drastically in a few years time.

General – for users and funding institutions

Emission inventories, sometimes called the 'engine house of environmental policies', are key to scenario studies and environmental policy development. A fair estimate of sources, strengths and distribution as well as trends in time, is a prerequisite for selecting cost-effective environmental policy packages and carrying out realistic studies on projections of future emissions. Moreover, atmospheric modellers need the best emission inventories as input into their models, and as modellers are often not experts on emission sources, the expertise of emission experts is key to providing these inventories required for good model performance. In contrast, dedicated and sustained support for global emission inventories is often not considered to be of great importance. Usually, studies on global emissions are financially supported on an ad hoc basis without the perspective of continuity.

The quality aspects of bottom-up different types of emission inventories have been analysed. The value of direct emission inventories such as EDGAR and other GEIA inventories has been demonstrated for validating the quality of national inventories, and the potential for verification of global, regional and national emission inventories by top-down inverse modelling. Emission inventories at global level are also required for checking for possible bias by comparing them with global budget constraints. Emission pat-

terns have also been shown to change dramatically, even in five-year periods. Without consideration of these changes, scientific and political conclusions drawn from analysis using emissions of outdated years as a proxy for present circumstances, as commonly done by modellers and policy makers, could give rise to substantial flaws. Emission inventories like EDGAR can also be used to link official country data with atmospheric models through conversion to the grid as part of an interaction between bottom-up and top-down evaluations of annual budgets as well as the trend in the budgets.

The importance for both policy and scientific applications of aspects like transparency, consistency, completeness, comparability and accuracy in global emission inventories results in the following recommendations:

- Sustained support for development, improvement and updating global emission inventories is required for integrating results of various studies on specific sources or regions. It is also necessary to provide a sound up-to-date basis for scientific and political analysis of emissions and emission trends. Apart from updating the inventories to more recent years, particular attention should also be given to the temporal and spatial distribution of the sources and changes of these patterns in time. Preliminary results showed the importance of seasonal and diurnal variation of a number of anthropogenic sources, in particular, of CH_4, CO, NO_x and NMVOC because of their chemical reactions in the troposphere.
- In the light of the presence of a number of sources with a relatively large uncertainty and the need for a prioritised inventory improvement plan, both for developing robust environmental policies and drawing up sound scientific conclusions, quantitative uncertainty assessments in national and global inventories should receive more attention. Although the focus of inventory development should remain at improving the emission estimates themselves, (expert-judged) uncertainty estimates have a key function in providing a quality label needed in comparisons of different emission estimates and in setting proper priorities in inventory improvements.
- Maintenance of global emission inventories is also a high priority for their function in providing a means of checking national inventories for comparability, consistency and transparency. Comparison of bottom-up emission estimates with global budget constraints for checking possible large biases in region or source totals is simple and should be recommended as a mandatory check, but can only be done for complete global inventories. In the combination of official national inventories supplemented with data from global inventories for missing countries, global inventories provide a means for this type of checking of national inventories.
- Since inverse modelling is one of the few independent approaches for verifying bottom-up inventories and the experience so far has proven its potential for some trace gases, further studies are needed. Such instruments as benchmarks of different models are recommended to better assess and quantify the uncertainty generated by the model structures. Simultaneous inverse modelling with more compounds than one is also advised to check activity data that are known to be very uncertain, such as the amount of biomass burning.
- The number of measurement stations should be expanded for improving the accuracy of inverse modelling results. Since atmospheric models require data from several countries, co-ordination at international level is highly recommended. Compounds that should receive more priority in consideration of verifying bottom-up inventories are CH_4 and the ozone precursors CO, NO_x and NMVOC. Another aspect of atmospheric measurements is continuity in established sites. For global and regional assessments of emission trends, but also for multi-year average runs, sustained support for present measurement sites for all globally or regionally relevant compounds is a high priority. The large stream of satellite observations that are currently becoming available also represent a powerful input for atmospheric models, but accurate calibration of these data will still require ground-based measurements. Sustained measurements of air concentrations will therefore remain to be key in independently verifying regional or global trends in emissions.

Finally, multi-gas trend inventories in atmospheric chemistry and transport models are important for studying the integrated effect on the chemical composition of the atmosphere. The importance for atmospheric chemistry stems from the fact that, generally, emissions of different reactive and long-lived trace gases show different trends over time and across regions. Since the trend in methane concentrations also depends on the presence and trends in emissions of ozone precursors, and because tropospheric ozone itself is also a greenhouse gas, multi-gas trend inventories are also important to study the relationship between tropospheric chemistry and climate change. Likewise, multi-gas data assimilation may also prove to be decisive in reducing the large uncertainties observed in the bottom-up emission estimates. As an example, one might think of reducing the uncertainty in the activity data of local and large-scale biomass burning, key sources at global or regional level emitting a handful of compounds simultaneously. This leads us again to conclude that integration of several

methods and approaches, including multiple trace gases and global or regional budget analysis, is probably the best way forward to achieving maximum accuracy and confidence in global bottom-up emission inventories. Yet, bottom-up emission inventories will forever remain the starting point (*a priori* estimate) and the end point (for comparisons of top-down *a postiori* estimates) of these analyses.

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Summary

This thesis deals with the quality of inventories of emissions to the atmosphere on the global scale. An emission inventory represents a compilation of estimates of amounts of one or more pollutants that have been emitted by different emission sources within a certain time period, e.g. one year. These source-specific figures refer to an area or a specific point of location and to a specific period in the past. A so-called 'bottom-up' inventory generally contains: (a) activity data for the source (e.g. petrol consumption (kg) in road transport for a specific year), (b) emission rates, also called 'emission factors' (e.g. kg N_2O per kg of petrol combustion of a passenger car), and (c) the location of the emission sources. Sometimes, an inventory also includes a temporal distribution of the emissions within the time period considered (e.g. seasonal variation). For this, data must either exist or will have to be obtained in some way. In cases where the emission rate is determined by many parameters, complex models may be required to calculate the emissions. Examples are delayed emissions from landfills and natural emissions with emission rates depending on local weather conditions.

Purpose of emission inventories

The purpose of emission inventories is to provide information for scientific or policy purposes. Scientists may use emission inventories to estimate or analyse the concentration and distribution of pollutants in the atmosphere, for example as input or as constraint to their air-transport and atmospheric chemistry models. These are otherwise constrained by datasets of air concentration measurements for specific points in time and space. Policy makers, on the other hand, are interested in monitoring the trend of emissions of pollutants, relevant for certain environmental themes such as acidification or climate change. They may also need to monitor progress in emission reductions strategies as agreed upon by national authorities or at international level, for example to check compliance with emission or air quality objectives as laid down in EU directives or UN protocols. Often policy makers are most interested in emissions inventories of man-made sources at national levels and for specific years. Scientists, however, are mostly interested in all sources – anthropogenic and natural – as well as in sinks (absorbers of chemical compounds from the air) at varying temporal and spatial scales.

Nevertheless, all data sources for estimating emissions have their limitations. This applies not only to datasets made available through the literature but also to one's own emission measurements. Providing a quality label to the data of the inventory is the only means to judge the applicability of the results, be it for scientific or for policy purposes. A key element of emission inventories is therefore a description of the quality – in terms of accuracy or uncertainty in a broad sense – of data that have been measured, calculated or otherwise derived.

Different approaches

Several ways exist of estimating emissions, each involving different approaches, methods, activities and spatial and temporal aggregation levels. In these thesis recent insights gained from knowledge on sources of global emissions to air of greenhouse gases and precursors of tropospheric ozone and aerosols are presented at various spatial and temporal aggregation levels:

- *Methodologies for estimating emissions*: so-called bottom-up and top-down approaches, of which the first are based on detailed descriptions of the sources and the second on estimates made on the basis of atmospheric data. A description and characterisation of these approaches is presented.
- *Types of emission research*: measurements, constructing inventories from activity data and emission factors, more complex modelling of (natural) emissions, estimation of source strength through so-called inverse modelling and inventory quality assessment such as verification.
- *Budgets, anthropogenic and natural emissions*: definitions, characteristics and relative importance to various compounds.

For compilation of global-gridded emission inventories different *bottom-up methods* are possible:

- Summation of ***official national inventories*** as reported to international bodies, e.g. acidifying gases and other pollutants having impacts on continental scale (*UN Economic Commission of Europe* (UN-ECE)) or emissions of greenhouse gases (*UN Climate Change Secretariat)*. These inventories have been compiled using bottom-up methods and most of them focus on national annual totals by source category, not on the spatial and temporal distribution.
- ***Direct estimation of emissions*** based on ***activity data at national level*** in international statistics, reported by international organisations such as the UN and the International Energy Agency (IEA), emission factors and other information reported in the literature, and grid maps of human-induced activities or land use to allocate emissions on a grid, e.g. EDGAR inventories of the RIVM and the

TNO, and the RAINS-ASIA inventories of the IIASA.

- Using a ***hybrid technique*** of combining the two mentioned approaches, by selecting a default global inventory (e.g. EDGAR) and replacing regions or countries for which more accurate, country-specific inventories are available (e.g. CORINAIR inventories in Europe).
- ***Direct estimation of emissions*** based on activity data for the ***global total statistics*** reported to international organisations and emission factors from the literature, with global total statistics divided over countries using a related surrogate variable such as gross domestic product (GDP) per country, total population per country or a similar activity for which country statistics are available and grid maps.
- ***Grid-based inventories***, notably for biogenic/ natural sources.

The focus of this thesis is on bottom-up methods, anthropogenic sources, global totals, gridded inventories and global/regional annual emission levels with a sectoral approach. 'Good practice' in achieving the requested inventory quality is described and analysed in this context:

- overview and definition of key quality aspects;
- relation to accuracy and uncertainty;
- quality assessments.

Practicalities are shown that determine the uncertainty and other quality aspects of global emission inventories: *availability* of activity data (years, countries), *applicability* to a specific source of emission factors and grid maps developed for a particular activity, as well as the *accuracy* or *uncertainty* of the three elements: activity data, emission factors and grid maps. The focus is on the analysis of the influence of these elements on inventory quality and on validation and verification of inventories. This is discussed both in general methodological terms and in practical applications.

Research questions

Four key scientific questions have been investigated:

1. **How does a user define the 'quality' of a global (or national) emission inventory?** (Chapter 2)
2. **What determines the quality of a global emission inventory?** (Chapter 2 and 7)
3. **How can inventory quality be achieved in practice and expressed in quantitative terms ('uncertainty')?** (Chapters 3 to 6)
4. **What is the preferred approach for compiling a global emission inventory, given the practical limitations and the desired inventory quality?** (Chapter 7 and 8)

The above questions are explored by analysing various approaches and methods, compiling global emission inventories in practice and reviewing all uncertainty elements to be considered when compiling global inventories. The practical applications refer to the construction of the so-called EDGAR emission inventories, which were developed as part of the Netherlands' National Research Programme on Global Air Pollution and Climate Change (NRP). This joint TNO-RIVM project, which started back in 1992, aimed at compiling a timely and consistent set of global anthropogenic emission inventories: the ***E****mission* ***D****atabase for* ***G****lobal* ***A****tmospheric* ***R****esearch*. At present the database comprises:

- direct greenhouse gases (CO_2, CH_4, N_2O) and the so-called F-gases, HFCs, PFCs and SF_6;
- ozone precursors (NO_x, CO and NMVOC); and CH_4, also an ozone precursor; and,
- selected aerosol precursors (SO_2 and NH_3); together with NO_x, also an aerosol precursor.

The last group also contributes to acidification of the soil.

Version 2 of this database, which covers global emissions by source for 1990, gridded at 1^ox1^o and at region/country level, was released in 1996 and has been extensively used worldwide, primarily by atmospheric modellers. It has triggered many questions by the science and policy communities. Version 3, released in the course of 2001 and

2002, covers direct greenhouse gases for the period of 1970 to 1995 and other compounds for 1990-1995 at grid, region and country level (www.rivm.nl/env/int/coredata/edgar). It has already been used to explore emission reduction potentials and options for emission trading within the Kyoto Protocol.

Elaboration

In Chapter 2 inventory quality is defined and discussed in relation to methodologies and approaches for inventory construction and selection of input data. The following quality aspects are introduced: *transparency* (clarity of source definitions and methods and data used by proper documentation), *consistency* (both across years and sources, and of source definitions, methods and data), *completeness* (of sources and years), *comparability* (between countries of methods and emission factors used, and of source definitions, also called 'absence of bias' = systematic, unexplained differences in comparable cases]), and *accuracy* (availability of an uncertainty estimate for the emission estimates, preferably in quantitative terms). In addition, a summary is presented of the sources of uncertainty and practical methods for estimating uncertainty in annual emis-

sions, as well as uncertainty in trends. These all build on the special character of most bottom-up emission inventories. The role and importance of validation (= check for the internal consistency and correctness) and verification (= comparison with independent data) of the emission inventory are also explained. Please note that in the literature these definitions are also used the other way around.

In Chapters 3 and 4 methods are presented that were used to compile a set of global gridded annual inventories of anthropogenic sources for 1990, called EDGAR 2.0, and a set of global annual inventories for several years, providing historical trends for 1970-1995, called EDGAR 3.2. The following elements have been included:

- *Rationale* - aiming at both source-specific gridded emissions and sectoral/regional emissions, which can be used for policy and scenario applications.
- *Conceptual approach* - database structure to consistently generate emissions for many different source categories both on grid and per region.
- *Methodology and data quality* - international statistics per country (sometimes the global total statistics to be divided over countries) (accuracy and completeness in years and countries), emission factors (quality, accuracy) and gridded maps to allocate national emissions within the country (quality, accuracy and applicability of the maps).
- *Validation and uncertainties* - comparison of global totals with IPCC estimates per main source category and order-of-magnitude uncertainty in the resulting global and regional emission, based on uncertainty estimates for activity data and emission factors.
- *Application of the dataset for scientific and policy purposes* - atmospheric modelling, inverse modelling and examples of policy support with results from the dataset.

The compilation of emission inventories *for a series of years* provides other, additional, aspects to be considered than for inventory construction for a single year. In general, consistency over time is an important quality aspect in evaluating the significance and consequences of emission trends. This is explored in Chapter 4, where an analysis is presented for the compilation of a new global inventory in the framework of EDGAR 3.2. This is applied to anthropogenic sources of methane for the period 1970-1995. Apart from the question of the accuracy of the emission estimate for a particular year, the question also arises about how robust the calculated emission trends are. In answering this question possible correlations between years need to be taken into account, certainly when the assumption is made that emission factors have remained constant over time. Chapter 5 provides an overview of existing inventories for natural sources and their uncertainty ranges.

In Chapter 6 quality assessment of global anthropogenic emission inventories is then discussed by comparing two different global inventories for CO_2 and reviewing the options available for validation and verification of national and international emission inventories. Then, in Chapter 7 a tiered approach for estimating and evaluating uncertainty in annual inventories and in emission trends in practice is presented, focussing on *national* inventories. In Chapter 7 the quality aspects encountered when compiling *global* emission inventories – both annual and in trends – as discussed in the previous chapters are also reviewed. Here, the basic sources of uncertainty, the relationships between sources and countries that need to be considered in view of possible correlations, characteristics of input data quality and data uncertainty are discussed.

Conclusions and recommendations

Chapter 8 summarises the answers to the first three research questions on the basis of the information presented in the previous chapters. This chapter also provides an answer to the last question on what the preferred approach is for compiling a global emission inventory. This is done in the context of the practical limitations discussed here (limited human resources and limited input data quality) and the desired inventory quality for atmospheric modellers and policy makers (a mixture of quality aspects as discussed in Chapter 2). Concluded here is that it is impossible to address all aspects simultaneously and reach a high quality standard for all. Each of the five bottom-up methods presented has its strong and weak elements. In other words, there is *a priori* no preferred method. Depending on which quality aspects are considered most important, one of the five methods presented will be most effective in meeting the specific quality requirements.

In addition, inventory compilers (and inventory users) are advised to be aware of key aspects when constructing (or using) a global or national emission inventory. Because emission inventories may be used for other purposes than for which they were constructed, a proper documentation of the inventory's quality – more than only the uncertainty in the emission figures provided – is recommended. The thesis concludes with recommendations to the scientific and policy-making community to give priority to inventory quality and quality assessment. Bottom-up emission inventories will forever remain the start point (*a priori* estimate for top-down studies) and the end point (for comparisons of top-down *a postiori* estimates) of these analyses.

Samenvatting

Dit proefschrift behandelt de kwaliteit van emissie-inventarisaties van de wereldwijde uitstoot (emissies) van stoffen naar de lucht. Een emissie-inventarisatie, of zoals men in het Brusselse zegt 'emissie-inventaris', is een verzameling van schattingen van de hoeveelheden van één of meer stoffen die geëmitteerd zijn door verschillende bronnen in een bepaalde tijd, bijv. een jaar. Deze bronspecifieke getallen hebben betrekking op een bepaald gebied of de locaties van zgn. puntbronnen en op een bepaalde historische periode. Om een zgn. 'bottom-up' inventarisatie te maken zijn de volgende onderdelen nodig: (a) gegevens over de activiteit van de bron (bijv. de hoeveelheid benzineverbruik door wegtransport in een bepaald jaar); (b) de uitstoot per tijdseenheid, ook 'emissiefactor' genoemd (bijv. kg N_2O per kg benzine die verbrand is in een personenauto); (c) de locatie van de emissiebronnen. Daarnaast wordt soms een profiel gemaakt van de variatie in de bronsterkte over de beschouwde periode (bijv. seizoensvariatie). Hiervoor is dus vereist dat deze informatie beschikbaar is of op een of andere wijze kan worden afgeleid. Als de emissiefactor wordt bepaald door vele verschillende eigenschappen van de bron dan zijn vaak meer complexe modellen nodig om de emissies te kunnen berekenen. Voorbeelden hiervan zijn vuilnisstortplaatsen, waaruit de emissies vertraagd tevoorschijn komen, en de emissies uit natuurlijke bronnen, waarvan de sterkte bepaald wordt door locale weersomstandigheden.

Het doel van emissie-inventarisaties

Emissie-inventarisaties worden gemaakt voor wetenschappelijke of beleidsmatige toepassingen. Wetenschappers kunnen deze informatie nodig hebben om de concentraties en verdeling van luchtverontreinigende stoffen in de atmosfeer te kunnen schatten of te analyseren. Een voorbeeld hiervan is het gebruik als invoer of als randvoorwaarde in hun modellen waarin het transport van de lucht (wind) en de atmosferische chemie (scheikundige reacties) tussen verschillende stoffen worden gesimuleerd. Beleidsmakers zijn geïnteresseerd in het volgen van de trend in de uitstoot van luchtverontreinigende stoffen, die van belang zijn voor bepaalde milieuthema's zoals verzuring van de bodem of klimaatverandering. Ze willen weten of de voortgang van emissiereducties in lijn is met de gemaakte afspraken op nationaal of internationaal niveau. Met andere woorden om te checken of het land voldoet – of op tijd gaat voldoen – aan de eisen voor uitstoot of luchtkwaliteit, zoals bijv. is vastgelegd in EU-richtlijnen of protocollen van de *Verenigde Naties* (Montreal voor CFK's etc., Kyoto voor broeikasgassen). Vaak zijn beleidsmakers alleen geïnteresseerd in emissie-inventarisaties van menselijke bronnen op nationaal niveau en voor specifieke jaren. Wetenschappers die de atmosfeer onderzoeken willen daarentegen meestal schattingen voor alle bronnen – dus ook natuurlijke – en 'sinks' ('putten' of onttrekkers van stoffen aan de lucht) en op verschillende ruimte- tijdschalen.

Echter alle databronnen voor emissies hebben hun beperkingen, niet alleen die door anderen gemaakt zijn maar ook eigen metingen (van emissies). De enige manier om de geschiktheid voor een bepaalde wetenschappelijke of beleidsmatige toepassing te kunnen vaststellen, is aan de hand van kwaliteitskenmerken van de verzameling getallen. Een essentieel onderdeel van emissie-inventarisaties is daarom de beschrijving van de kwaliteit van de gerapporteerde data – die gemeten, berekend of op andere wijze afgeleid zijn – in termen van nauwkeurigheid of van onzekerheid in een breder verband.

Verschillende invalshoeken en methoden

Er zijn diverse manieren om emissies te schatten, ieder met een eigen aanpak, methodiek, benadering, en aggregatieniveau in ruimte en tijd (stad, provincie, land, wereld; dag, week, maand, jaar). In dit proefschrift worden recente inzichten beschreven in de mondiale emissies naar de lucht van directe broeikasgassen en van de zgn. 'voorlopers' van troposferisch ozon (ozon in de onderste luchtlagen tot ca. 10-15 km hoogte) en van aërosolen (kleine deeltjes zoals fijn stof). Deze beschrijving wordt gegeven voor verschillende ruimtelijke niveaus (mondiaal, wereldregio, land, 1x1 graad gridcel) en tijdschalen (1 jaar; 25 jaar):

- *Methodieken om emissies te schatten*: de zgn. 'bottom-up'-methode (detailbeschrijving van bronnen) en 'top-down'-methode (schatting vanuit atmosfeergegevens), waarvan een beschrijving en karakterisering gegeven wordt;
- *Types van emissieonderzoek*: metingen, samenstelling van een inventarisatie met behulp van activiteitendata en emissiefactoren, meer ingewikkelde modellering van (natuurlijke) emissies, schatting van bronsterkte door zgn. inverse modellering (met 'omgekeerde' berekeningen, uit gemeten concentraties in de lucht), kwaliteitsonderzoek van emissie-inventarisaties;
- *Budgetten, door de mens veroorzaakte emissies versus natuurlijke bronnen*: karakteristieken, definities en relatief belang voor verschillende stoffen.

Voor het maken van mondiale emissie-inventarisaties op gridcel-niveau zijn verschillende bottom-up-methoden mogelijk:

- ***samenvoegen van officiële nationale emissie-inventarisaties***, bijv. die voor verzurende stoffen voor de *Economische Commissie voor Europa* van de VN (UN-ECE) worden opgesteld of voor broeikasgassen voor het *Klimaatsecretariaat van de VN*. Deze inventarisaties zijn opgesteld volgens een bottom-up methodiek en de meeste geven alleen nationale jaartotalen per broncategorie, zonder verdere details in ruimte en tijd.
- ***directe schatting van emissies*** met behulp van (a) ***activiteitendata op landniveau*** uit internationale statistieken (bijv. van de *Verenigde Naties* en het *Internationaal Energie Agentschap* (IEA), (b) emissiefactoren en andere informatie uit de literatuur, en (c) wereldkaarten om de emissies over gridcellen te kunnen verdelen (bijv. met locaties van menselijke activiteiten of bodemtypen). Voorbeelden hiervan zijn de EDGAR-inventarisaties van RIVM en TNO en de RAINS-inventarisaties van het *Internationaal Instituut voor Toegepaste Systeem Analyse* (IIASA).
- een ***hybride techniek*** door combinatie van de twee bovenstaande aanpakken. Eerst wordt een standaard mondiale emissie-inventarisatie gekozen (bijv. EDGAR) en daarna worden de emissies voor bepaalde wereldregio's of landen vervangen door meer nauwkeurige, landspecifieke inventarisaties (bijv. CORINAIR-inventarisaties voor Europa).
- ***directe schatting van emissies*** gebaseerd op ***activiteitendata op mondiaal niveau*** uit statistieken voor wereldtotalen die door internationale organisaties worden opgesteld (bijv. CFK-gebruik door AFEAS, een organisatie waarin de chemische industrieën samenwerken) en emissiefactoren uit de literatuur en wereldkaarten. Hierbij wordt de wereldtotalen verdeeld over de afzonderlijke landen met een geselecteerde andere activiteit als verdeelsleutel, waarmee een proportionele verhouding verondersteld wordt (bijv. het bruto nationaal product per land, de bevolking per land of een andere grootheid waarvoor internationale landenstatistieken beschikbaar zijn).
- ***inventarisaties op grid-niveau***, in het bijzonder voor natuurlijke en levende bronnen.

De nadruk in dit proefschrift ligt op bottom-up methodieken, menselijke bronnen, wereldtotale emissies, inventarisaties op een grid, en mondiale/regionale jaarlijkse emissies, en dit alles per broncategorie. In dit verband wordt een 'goede praktijkaanpak' beschreven om de gevraagde inventarisatiekwaliteit in kaart te brengen:

- een overzicht en definitie van de belangrijkste kwaliteitsaspecten;
- de relatie met nauwkeurigheid/onzekerheid;
- kwaliteitsonderzoek en –analyse.

Toegelicht wordt welke zaken in de praktijk de onzekerheid en andere kwaliteitskenmerken van mondiale emissie-inventarisaties bepalen: *beschikbaarheid* van activiteitendata (jaren, landen), *toepasbaarheid* voor een bepaalde bron van emissiefactoren en wereldkaarten voor een bepaald onderwerp, en de *nauwkeurigheid* of *onzekerheid* voor deze drie onderdelen: activiteitendata, emissiefactoren en kaarten. De nadruk ligt op analyse hoe deze elementen de kwaliteit van een emissie-inventarisatie beïnvloeden en hoe inventarisaties kunnen worden geverifieerd en gevalideerd. Dit wordt zowel methodologisch onderzocht als in toepassingen in de praktijk.

Onderzoeksvragen

De volgende vier onderzoeksvragen worden in dit proefschrift onderzocht:

1. **Hoe definieert een gebruiker de kwaliteit van een mondiale (of nationale) emissie-inventarisatie?** (Hoofdstuk 2)
2. **Waardoor wordt de kwaliteit van een mondiale emissie-inventarisatie bepaald?** (Hoofdstuk 2 en 7)
3. **Hoe kan in de praktijk een bepaalde kwaliteit van een emissie-inventarisatie worden gerealiseerd en hoe kan die kwantitatief worden uitgedrukt ('onzekerheid')?** (Hoofdstuk 3 tot en met 6)
4. **Welke aanpak heeft de voorkeur voor het construeren van een mondiale emissie-inventarisatie, rekeninghoudend met de beperkingen in de praktijk en de gewenste kwaliteit van de inventarisatie?** (Hoofdstuk 7 en 8)

Het antwoord op deze vragen wordt gegeven door het analyseren van verschillende methodieken en wijzen van aanpak, door de constructie van emissie-inventarisaties in de praktijk en door beoordeling van de belangrijkste elementen van onzekerheid die beschouwd zouden moeten worden bij de compilatie van mondiale emissie-inventarisaties. De praktische toepassing is de constructie van de zogenoemde EDGAR-emissie-inventarisaties, die als onderdeel van het *Nationaal Onderzoekprogramma Mondiale Luchtverontreiniging en Klimaatverandering* ontwikkeld zijn. Dit gezamenlijke TNO-RIVM-project, dat oorspronkelijk gestart is in 1992 na een voorstudie door TNO in 1991, had als doel een actuele en consistente mondiale emissie-inventarisatie te maken voor wetenschap en beleid: de ***E**mission **D**atabase for **G**lobal **A**tmospheric **R**e-*

search (Emissie Database voor Mondiaal Atmosferisch Onderzoek). Thans bevat EDGAR de volgende stoffen:

- **directe broeikasgassen**: *kooldioxide* (CO_2, met name door verbranding van kolen, olie en gas), *methaan* (CH_4, met name uit de winning en transport van kolen, aardgas – dat zelf voornamelijk uit methaan bestaat – en aardolie, uit herkauwers, vuilnisstortplaatsen en afvalwater, en verbouw van rijst), *lachgas* (N_2O, met name uit dierlijke mest, gebruik van kunstmest en industriële productie van salpeterzuur en adipinezuur, een grondstof voor nylon), en de zgn. *F-gassen* (HFK's, met name voor koelinstallaties en als isolatiemiddel, PFK's, een bijproduct van aluminiumproductie, en SF_6, vooral gebruikt in hoogspanningsschakelaars).
- **voorlopers van ozon**: *stikstofoxiden* (NO_x vooral afkomstig uit wegverkeer en elektriciteitsproductie), *koolmonoxide* (CO, met name door savannabranden en tropische bosbranden, wegverkeer en het gebruik van brandhout), en *vluchtige organische stoffen* (VOS, vooral uit wegverkeer, gebruik van oplosmiddelen, olieproductie, gebruik van brandhout en branden van savanna's, landbouwafval en bossen); ook *methaan* is een voorloper van ozon.
- **voorlopers van aërosolen (selectie):** *zwaveldioxide* (SO_2, vooral door verbranding van steenkool en door kopersmelterijen) en *ammoniak* (NH_3, met name uit dierlijke mest en gebruik van kunstmest). Deze stoffen dragen, tezamen met stikstofoxiden die ook voorloper van aërosolen zijn, ook bij aan verzuring van de bodem.

Versie 2 van de database werd in 1996 op het internet geplaatst en is uitgebreid en wereldwijd gebruikt, vooral door atmosferisch-chemische modelleurs, en heeft tot veel verzoeken en reacties uit wetenschap en beleid geleid. Versie 3.2, die in de loop van 2001 en 2002 op het internet geplaatst is (www.rivm.nl/env/int/coredata/edgar), bevat wereldwijde emissies van de directe broeikasgassen voor de periode 1970-1995 en voor de andere stoffen voor 1990-1995, zowel op een 1x1 graden grid als op land- en regioniveau. Deze informatie is reeds gebruikt om de mogelijkheden te onderzoeken voor emissiereductie en emissiehandel in het buitenland in het kader van de mogelijkheden onder het Kyoto Protocol over de beperking van de uitstoot van broeikasgassen.

Uitwerking

In Hoofdstuk 2 wordt het begrip 'kwaliteit' van emissie-inventarisaties gedefinieerd. Dit wordt besproken in het kader van de methoden en wijzen van aanpak voor de constructie van emissie-inventarisaties en de selectie van inputgegevens. Als kwaliteitskenmerken worden geïntroduceerd: *transparantie* (duidelijkheid in de definitie van broncategorieën, berekeningsmethoden en gebruikte gegevens door een volledige documentatie), *consistentie* (gebruik van dezelfde brondefinities, methoden en type gegevens voor alle jaren en tussen bronnen), *compleetheid* (van bronnen en jaren), *vergelijkbaarheid* (tussen landen, van methoden en emissiefactoren en van brondefinities, ook wel genoemd het ontbreken van 'bias' [= systematische, onverklaarde verschillen in vergelijkbare gevallen]) en *nauwkeurigheid* (schatting van de onzekerheid in de gerapporteerde emissies, bij voorkeur kwantitatief door de opgave van een onzekerheidsinterval). Daarnaast worden de verschillende typen van oorzaken van onzekerheid (onnauwkeurigheid) besproken evenals praktijkmethoden om de onzekerheid te schatten in de emissies van een bepaald jaar en in de emissietrend over een reeks van jaren. Bij deze praktijkmethoden wordt gebruik gemaakt van de speciale kenmerken van de meeste 'bottom-up' emissie-inventarisaties. Verder wordt de rol en het belang toegelicht van validatie (= checken van de interne consistentie: gebruik van de juiste inputdata en formules, correctheid van berekeningen) en verificatie (= controle van de gerapporteerde emissies of emissietrends door vergelijking met onafhankelijk gemaakte emissieschattingen). Deze begrippen worden in de literatuur overigens ook vaak omgekeerd gebruikt.

In de Hoofdstukken 3 en 4 wordt de praktijkaanpak besproken voor de compilatie van een verzameling van mondiale emissie-inventarisaties op een grid voor 1990 van menselijke bronnen (EDGAR 2.0) en van mondiale inventarisaties van de historische trend in de periode 1970-1995 (EDGAR 3.2). Hierbij worden de volgende aspecten bediscussieerd:

- *Uitgangspunten* – het doel was om per broncategorie de mondiale emissies zowel op een 1x1 graden grid te hebben als emissies uitgesplitst per regio zodat ze bruikbaar zijn voor zowel wetenschap als beleid;
- *Conceptuele aanpak* – de structuur van de database dient op consistente wijze de emissies voor vele verschillende broncategorieën zowel op grid als per regio te kunnen genereren;
- *Methodiek en gegevenskwaliteit* – internationale statistieken per land (soms mondiale totalen, die over landen verdeeld worden) (onzekerheid en compleetheid in jaren en landen), emissiefactoren (kwaliteit, onzekerheid), wereldkaarten op 1x1 graden grid, die nodig zijn om nationale emissies binnen de landen te verdelen (kwaliteit, onzekerheid en toepasbaarheid voor de betreffende bron);
- *Validatie en onzekerheden* – vergelijking van mondiale totalen met schattingen per hoofd-

broncategorie gepubliceerd door het *Intergovernmental Panel on Climate Change* (IPCC) en ordegrootte schatting van de onzekerheid in de resulterende mondiale en regionale totale emissies, gebaseerd op onzekerheidschattingen voor de gebruikte activiteitendata en emissiefactoren;

- *Toepassing van de inventarisatie voor wetenschappelijke en beleidsmatige doelen* – atmosfeermodellering, inverse modellering en voorbeelden van beleidsondersteuning met resultaten van de EDGAR datasets.

De compilatie van emissie-inventarisaties voor een reeks van jaren vraagt om onderzoek van andere aspecten dan die nodig zijn voor de constructie van een inventarisatie voor één jaar. Om de significantie en consequenties van berekende emissietrends te kunnen beoordelen is de consistentie tussen de jaren een belangrijk kwaliteitskenmerk. Dit wordt nader onderzocht in Hoofdstuk 4, waar de analyse besproken wordt die gemaakt is als onderdeel van de aanpak van de constructie van een nieuwe mondiale emissie-inventarisatie in het kader van EDGAR 3.2 van menselijke methaanbronnen voor de periode 1970-1995. Naast de vraag wat de nauwkeurigheid is van de emissieschattingen voor een bepaald jaar, wordt hier de vraag onderzocht hoe robuust de berekende trends zijn. Voor het beantwoorden van deze vraag moeten mogelijke correlaties tussen jaren worden onderzocht, zeker wanneer de veronderstelling gebruikt is dat de emissiefactoren in de loop der tijd niet veranderd zijn. Vervolgens wordt in Hoofdstuk 5 een overzicht gegeven van bestaande mondiale emissie-inventarisaties voor natuurlijke bronnen en de onzekerheidsschattingen hiervoor.

Hierna wordt in Hoofdstuk 6 de kwaliteitsanalyse besproken van mondiale antropogene emissie-inventarisaties. Dit wordt gedaan door een systematische vergelijking van twee verschillende mondiale inventarisaties voor CO_2 en door inventarisatie van de beschikbare opties voor validatie en verificatie van nationale en internationale emissie-inventarisaties. Tenslotte wordt in Hoofdstuk 7 een getrapte aanpak gepresenteerd om in de praktijk de onzekerheden te schatten en te evalueren in jaarlijkse emissies en in de meerjarentrend, waarbij het accent ligt op nationale emissie-inventarisaties. Vervolgens worden in dit hoofdstuk de kwaliteitsaspecten geïnventariseerd die van belang zijn bij de constructie van mondiale emissie-inventarisaties, zowel voor een bepaald jaar als voor meerjarentrends, en die in de voorgaande hoofdstukken besproken zijn. Daarbij worden onder andere besproken: de oorzaken van onzekerheid, de relaties tussen bronnen en landen die onderzocht moeten worden in verband met mogelijk correlaties, en de karakterisering van de kwaliteit van de gebruikte gegevens en hun onzekerheid.

Conclusies en aanbevelingen

In Hoofdstuk 8 worden de antwoorden op de eerste drie onderzoeksvragen uit Hoofdstuk 1 samengevat, die in de voorgaande hoofdstukken gepresenteerd zijn. Ook wordt antwoord gegeven op de laatste vraag welke aanpak de voorkeur heeft bij de constructie van een mondiale emissie-inventarisatie. Dit wordt gedaan rekening houdend met de praktische beperkingen die in dit proefschrift besproken zijn (beperkte capaciteit en beperkte kwaliteit van de beschikbare gegevens) en de gewenste kwaliteit voor wetenschappers en beleidsmakers (een mix van de kwaliteitskenmerken die in Hoofdstuk 2 besproken zijn). De conclusie luidt, dat het onmogelijk is alle aspecten tegelijk even goed te kunnen adresseren. Elke bottom-up-aanpak heeft zijn intrinsiek sterke en zwakke kanten (zie Tabel 8.1). Met andere woorden, er is *a priori* geen 'voorkeursaanpak'. Afhankelijk van aan welke aspecten in de toepassing het meeste belang wordt gehecht, zal één van de vijf gepresenteerde mogelijkheden het meest effectief aan de kwaliteitseisen tegemoet kunnen komen. Omdat emissie-inventarisaties soms op andere wijze gebruikt worden dan waarvoor ze gemaakt zijn, is een goede documentatie van de kwaliteitkenmerken – meer dan alleen een onzekerheid van de emissies – aan te bevelen. Daarom wordt dit hoofdstuk afgesloten met aanbevelingen voor zowel wetenschappers als beleidsmakers over de prioriteit die aan de kwaliteit en kwaliteitsonderzoek van emissie-inventarisaties gegeven zou moeten worden. *Bottom-up* emissie-inventarisaties zullen altijd het startpunt blijven ('*a priori*' schattingen voor 'top-down'-modelstudies) en het eindpunt (voor vergelijking van de '*a postiori*' resultaten van 'top-down'-studies) van integrale emissie-analyses.

Abbreviations

AD	Activity Data
AFEAS	Alternative Fluorocarbons Environmental Acceptability Study
AGO	Australian Greenhouse Office
AL	Activity Level
AP-42	Air Pollutant report of EPA; Fourth Edition (US Handbook of Emission Factors)
ARCS	Austrian Research Centers Seibersdorf
cap	capita (person)
CBS	Statistics Netherlands
CDIAC	Center for Dissemination and Analysis of Carbon dioxide
CEC	Commission of the European Communities
CIS	Commonwealth of Independent States (i.e. former USSR)
CITEPA	Centre Interprofessionel Technique d'Etudes de la Pollution Atmospherique
COD	Chemical Oxygen Demand (of organics loading)
CORINAIR	CORe INventory AIR emissions
CRF	Common Reporting Format (of emission data files, annexed to a NIR)
CTM	Chemical Transport Model
DETR	Department for Transport, Local Government and the Regions
dm	dry matter
DOC	Degradable Organic Carbon
ECE	Economic Commission for Europe (UN)
EDGAR	Emission Database for Global Atmospheric Research (of RIVM and TNO)
EEA	European Environment Agency
EF	Emission Factor
EFTEC	Economics for the Environment Consultancy
EIT	Economies-In-Transition (country group comprising the former SU and Eastern Europe)
EM	Emissions
EMEP	European programme for Monitoring and Evaluation of long-range transmission of air Pollutants
EPA	US Environmental Protection Agency
ERG	Eastern Research Group
ETC/ACC	European Topic Centre on Air and Climate Change
ETC/AE	European Topic Centre on Air Quality and Emissions (now ETC/ACC)
EU	European Union
F	Fraction of methane in landfill gas
FAO	Food and Agricultural Organisation (UN)
FCCC	Framework Convention on Climate Change (UN)
F-gases	Group of fluorinated compounds comprising HFCs, PFCs and SF_6
FTP	File Transfer Protocol
GDP	Gross Domestic Product (of a country)
GEIA	Global Emissions Inventory Activity (of IGAC)
GISS	Goddard Institute for Space Studies (of NASA)
GNP	Gross National Product (of a country)
GOME	Global Ozone Monitoring Experiment
GUM	Guide to the Expression of Uncertainty in Measurements (of ISO)
GVFI	Global Vegetation Fire Inventory
ICSG	International Copper Study Group
IEA	International Energy Agency
IFA	International Fertiliser Industry Association
IGAC	International Global Atmospheric Chemistry programme
IGBP	International Geosphere-Biosphere Programme
IIASA	International Institute for Applied Systems Analysis
IISI	International Iron and Steel Institute

ILZSG	International Lead and Zinc Study Group
IMAGE	Integrated Model to Assess the Greenhouse Effect (of RIVM)
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
ISIC	International Standard Industrial Code
LDC	Less Developed Countries (region comprising all countries except OECD'90 and EIT)
LHV	Lower Heating Value
Ln	Natural logarithm
LOTOS	Long-Term Ozone Simulation (model of TNO)
MCF	Methane Conversion Factor
MEP	TNO Environment, Energy and Process Innovation
MSW	Municipal Solid Waste
NA	Not Available; Not Applicable; also: Nitric Acid
NAPAP	National Acid Precipitation Assessment Programme
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NGO	Non-Governmental Organisation
NIR	National Inventory Report (annual greenhouse gas inventory report to the UNFCCC)
NRP-MLK	Dutch National research Programme on Global Air Pollution and Climate Change
OECD	Organisation for Economic Cooperation and Development
OECD'90	Country group according to the OECD composition in 1990 (exclusive of newest members)
OLADE	Organizacion LatinoAmericana de Energia (Latin American Energy Organisation)
ORNL	Oak Ridge National Laboratory (home of CDIAC)
PHOXA	Photochemical Oxidant and Acid Deposition (model of TNO)
POET	Precursors of Ozone and their Effects on the Troposphere (EU project)
PPP	Purchasing Power Parity (conversion rate to US$, kind of 'hamburger conversion rate')
PVC	Poly vinyl chloride
QA	Quality Assurance
QC	Quality Control
RAINS-ASIA	Regional Air Pollution INformation and Simulation (model developed by IIASA)
SBSTA	Subsidiary Body for Scientific and Technological Advice (of Parties to the UNFCCC)
SCIAMACHI	SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY
SU	Soviet Union
TA	Treated Anaerobically (fraction of wastewater)
TCCCA	Transparancy-Consistency-Completeness-Comparability-Accuracy
TNO	Netherlands Organisation for Applied Scientific Research
TSU	Technical Support Unit (of IPCC)
U	Uncertainty
UBA	Umwelt Bundes Ambt (German Environmental Protection Agency)
UF	Uncertainty Factor
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nation's Framework Convention on Climate Change
UNSD	United Nation's Statistical Division
US-BoM	US Bureau of Mines (now: USGS)
USGS	US Geological Survey
VROM	Netherlands' Ministry of Housing, Spatial Planning and the Environment
WG I	Working Group I (of IPCC)
WMO	World Meteorological Organisation
WRI	World Resources Institute
WUR	Wageningen University and Research Centre
WWTP	Waste Water Treatment Plant

Chemical compounds

BrO_2	Bromine oxide
C	Carbon (element basis)
CFCs	Chlorofluorocarbons (e.g. CFC-11, 12, also called R-11, R-12)
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CTC	Carbon Tetra Chloride (CCl_4)
HCFCs	Hydrochlorofluorocarbons
HCHO (CH_2O)	Formaldehyde (methanal)
HFCs	Hydrofluorocarbons (e.g. HFC-134a, also called R-134a)
HNO_3	Nitric Acid
H_2SO_4	Sulphuric Acid
H_2O	Water (vapour)
N	Nitrogen (element basis)
NA	Nitric Acid
NH_3	Ammonia
NH_3-N	Ammonia, expressed as N (element)
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen oxide (NO and NO_2), expressed as NO_2
NO_x-N	Nitrogen oxide (NO and NO_2), expressed as N (element)
NO_2	Nitrogen dioxide
N_2O	Nitrous oxide
N_2O-N	Nitrous oxide, expressed as N (element)
O_3	Ozone
OClO (ClO_2)	Chlorine dioxide
OH	Hydroxyl
PFCs	Perfluorocarbons (e.g. CF_4, C_2F_6)
S	Sulphur (element basis)
SF_6	Sulphur hexafluoride
SO_2	Sulphur dioxide
VOC	Volatile Organic Compounds (may include [VOC] or exclude methane [NMVOC])

Units

MJ	Mega Joule (10^6 Joule)
GJ	Giga Joule (10^9 Joule)
TJ	Tera Joule (10^{12} Joule)
PJ	Peta Joule (10^{15} Joule)
EJ	Exa Joule (10^{18} Joule)
Mg	Mega gramme (10^6 gramme)
Gg	Giga gramme (10^9 gramme)
Tg	Tera gramme (10^{12} gramme)
Pg	Peta gramme (10^{15} gramme)
ton	metric tonne (= 1 000 kilogramme = 1Mg)
kton	kiloton (= 1 000 metric tonne = 1 Gg)
Mton	Megaton (= 1 000 000 metric tonne = 1 Tg)
yr	year

Curriculum Vitae

Jos Olivier werd in 1956 geboren in Wijk aan Zee (gemeente Beverwijk) onder de rook van de Hoogovens. In 1974 behaalde hij aan het Pius X College te Beverwijk bij de eerste lichting van de zgn. Mammoet-wet het Atheneum-B diploma. Enthousiast geworden door zijn leraar Natuurkunde is hij daarna Natuurkunde gaan studeren aan de Vrije Universiteit in Amsterdam. Daarnaast was hij enkele jaren actief als bestuurslid van de bewonersraad van het studentencomplex 'Uilenstede' in Amstelveen, resp. als lid van het Algemeen Bestuur van de Stichting Studentenhuisvesting. In 1984 is hij afgestudeerd bij Prof.dr. H.J. Boersma en Dr. M. Thies met als hoofdvak (theoretische) natuurkunde en als bijvak onderdelen der wiskunde en bestuurskunde. Zijn belangstelling voor duurzame energie, onder andere tot uitdrukking komend in een doctoraal-colloquium over tipvanes bij windturbines, leverde hem de bijnaam 'Jos windmolen' op.

Zijn eerste vaste werkkring was als coördinator multidisciplinair energie-onderzoek en -onderwijs bij de Technische Universiteit Delft (TU Delft). Daar hield hij zich hij van 1985 tot 1989 bezig met het stimuleren en initiëren van interdisciplinaire samenwerking tussen de vakgroepen die zich met energie-onderzoek bezighouden, ondermeer via contract-research bij de EU en bij Novem op het terrein van windenergie, ondergrondse kolenvergassing en andere geavanceerde technologieën op het gebied van produktie en gebruik van fossiele energie.

Vervolgens was hij in 1989-1990 als stafmedewerker verbonden aan de Algemene Energie Raad (AER) in Den Haag, een adviesorgaan voor de Minister van Economische Zaken, waar hij zich bezig hield met de ambtelijke voorbereiding van adviezen onder meer over energiebeleid en duurzame ontwikkeling naar aanleiding van het Brundlandt-rapport '*Our Common Future*' en het (eerste) Nationaal Milieubeleidsplan, mede als reactie op het RIVM-rapport '*Zorgen voor Morgen*'.

De nationale impact van dit rapport heeft hem zijn volgende baan bezorgd, namelijk vanaf 1990 als senior onderzoeker mondiale emissies en coördinator 'energie internationaal', bij het Rijksinstituut voor Volksgezondheid en Milieu (RIVM) in Bilthoven. Hier was hij verantwoordelijk voor de energie- en industrie-emissies in de eerste nationale inventarisatie in 1991 van broeikasgasemissies, en heeft bijgedragen aan advisering van het Ministerie van VROM, EU, UNEP en OECD/IEA over beleidsopties voor de reductie van broeikasgasemissies, waaronder mondiale luchtvaart, en de verdere ontwikkeling van de energie/emissie-scenariomodule in RIVM's geïntegreerde klimaatmodel 'IMAGE'. Daarnaast was hij projectleider van de ontwikkeling en update van de *Emission Database for Global Atmospheric Research* (EDGAR), een gezamenlijk TNO-RIVM-project. EDGAR is ontwikkeld in samenwerking met een groot aantal internationale instituten zoals en als bijdrage aan de *Global Emission Inventory Activity* (GEIA), een onderdeel van het *International Global Atmospheric Chemistry Programme* (IGAC). Naast zijn werk voor het RIVM heeft hij zijn cijfermatige expertise ook nog enige jaren aangewend als penningmeester van de Organisatie voor Duurzame Energie (ODE) en de Stichting Windenergie Conferentie Nederland (SWEC) van de Nederlandse Windenergie Vereniging (NEWIN).

Vanaf 1995 tot heden is hij senior onderzoeker internationale emissies en coördinator van de groep 'internationale emissies' bij het RIVM. Als zodanig coördineerde hij de productie van de tweede '*National Communication of Climate Change Policies*' van Nederland voor het VN-Klimaatverdrag en coördineerde hij de afgelopen jaren de nationale rapportages van broeikasgasemissies voor het Klimaatverdrag en de Europese Unie. Naast zijn deelname aan de IGAC/GEIA-groepen voor CO_2, CH_4 and N_2O en Data Management, is hij sinds 1998 co-convener van GEIA. Hij nam als lid of co-voorzitter namens Nederland deel aan verschillende Expert Groups van het *Intergovernemental Panel on Climate Change* (IPCC) en van het *VN-Klimaatverdrag* en *Kyoto Protocol* over inventarisatie en rapportage van broeikasgasemissies.

Na de publicatie van een reeks artikelen over mondiale en nationale emissie-inventarisaties, besloot de doctorandus in het voorjaar 2001 het voorbeeld van andere RIVM-collega's te volgen en zijn status te veranderen in promovendus en een selectie van publicaties te verwerken tot een proefschrift, daarbij gesteund door zijn promotoren prof.dr.ir. P.J.H. Builtjes en prof.dr. L. Hordijk.

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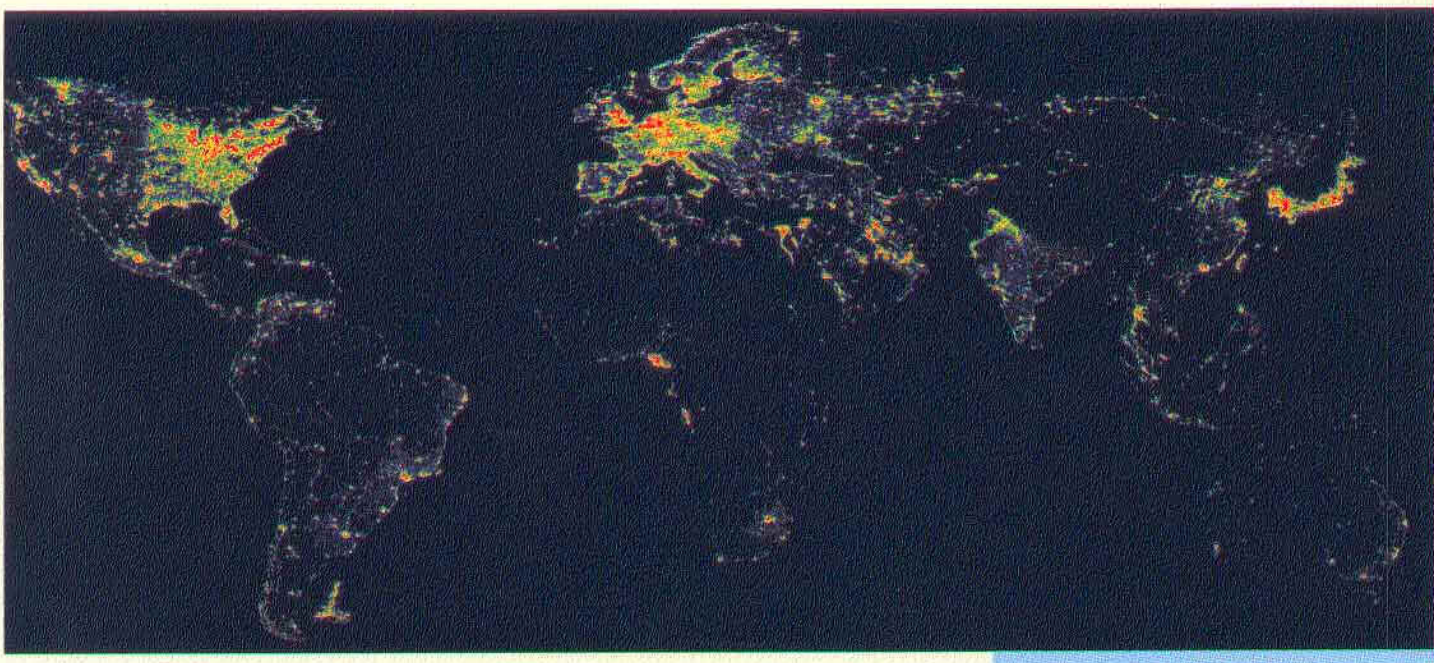
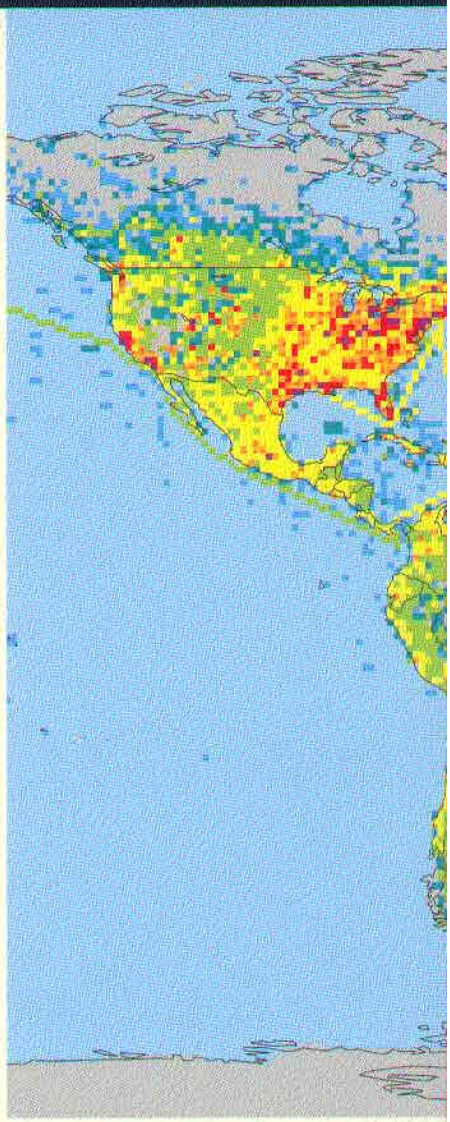


Jos Olivier trained at the Free University in Amsterdam in physics. He has worked for four years as co-ordinator of multidisciplinary energy research at the Delft University of Technology (TU Delft) and one year as staff member at the Dutch General Energy Advisory Council (AER), which advises the Minister of Economic Affairs on energy policy issues. Since 1990, Jos Olivier works at the Netherlands National Institute for Public Health and the Environment (RIVM) as senior scientist and co-ordinator of international emission inventories, with a special interest in energy-related topics. He is project leader of the joint TNO-RIVM project on the construction and maintenance of the EDGAR information system (Emission Database for Global Atmospheric Research). He was co-ordinator of the Netherlands' Second National Communication for the UN *Framework Convention on Climate Change* (UNFCCC) and participated in workshops of the UNFCCC secretariat on methodological, reporting and validation issues related to national emission inventories. Currently, he is co-convenor of the *Global Emission Inventory Activity* (GEIA) of the *International Global Atmospheric Chemistry* programme (IGAC) of IGBP, a research network of people active in the field of constructing global inventories, and also participates in various Expert Groups on Compiling and Managing Emission Inventories of the *National Greenhouse Gas Inventory Programme* (NGGIP) of the Technical Support Unit for Greenhouse Gas Inventories of the *Intergovernmental Panel on Climate Change* (IPCC) and of the *UN Framework Convention on Climate Change* (Climate Convention, UNFCCC).



Front cover: *EDGAR 3.2 Map of Carbon Dioxide Emissions from Fossil Fuel and Biofuel Combustion in 1995*. Including international shipping emissions and aircraft emissions below 1 km altitude. Biofuel emissions tentatively calculated at 10% of the gross emissions to account for an assumed 10% unsustainable production.

Back cover: *World Map of Artificial Sky Brightness**. Blue border indicates artificial sky brightness over 10% than the natural brightness; yellow indicates artificial sky brightness equal to the natural so that the total sky brightness is doubled.

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