Compilation of Regional to Global Inventories of Anthropogenic Emissions

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1. INTRODUCTION

The mathematical modelling of the transport and transformation of trace species in the atmosphere is one of the scientific tools currently used to assess atmospheric chemistry, air quality, and climatic conditions. One of the most important inputs to such models are accurate inventories of emissions of the trace species included in the study at the appropriate sectoral, spatial, temporal, and species resolution. In addition, from the management perspective detailed information on emissions is also required at high resolution for the design of policies aimed at reducing emissions of pollutants, and for the evaluation of the efficiency of such policies.

The compilation of emissions information for scientific use started in the 1970s for oxides of sulphur and nitrogen. These initial inventories calculated global emissions by large geographic areas (Várhelyi, 1985), with very little spatial and temporal resolution. In the last three decades a wealth of information has been developed on anthropogenic activities and their emissions; however, these statistics must be used wisely to provide a picture of the desired quantities.

Sections 2 to 4 present an overall description of the current methodologies used to compile regional to global inventories of anthropogenic emissions. This discussion is by no means exhaustive; rather it attempts to give the reader an overview of how emissions from anthropogenic sources were and are being estimated (Baldasano and Power, 1998). As discussed in chapter 4, these methodologies can also be applied to

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the estimation of emissions from biogenic sources. Section 5 describes examples of regional and global inventories that are currently used in studies of the composition of the atmosphere at different spatial scales, and Section 6 discusses the development of inventories representing anthropogenic emissions over the past decades.

2. INVENTORY DEVELOPMENT

There are two general methodologies used to estimate regional to global emissions: bottom-up and top-down. Bottom-up methodologies apply the following general equation to estimate emissions:

$$E_i = A_i (EF)_i P_{1i} P_{2i} \ldots\ldots$$

where E_i are emissions (for example, kg sulphur hr^{-1}), A_i is the activity rate for a source (or group of sources *i*, for example, kg of coal burned in a power plant), $(EF)_i$ is the emission factor (amount of emissions per unit activity, for example, kg sulphur emitted per kg coal burned), and P_{1i}, P_{2i} ... are parameters that apply to the specified source types and species in the inventories (for example, sulphur content of the fuel, efficiency of the control technology). Top-down methodologies, also known as inverse modelling, derive emissions estimates by inverting measurements in combination with additional information, such as the results of atmospheric transport and transformation models. The top-down methodologies are discussed in detail in chapters 11 and 12.

3. USE OF BOTTOM-UP METHODOLOGIES TO ESTIMATE EMISSIONS

The three major inputs needed to apply this methodology are the locations of the sources, the activity rates, and the emission factors. To estimate the emissions of certain trace species additional parameters are needed. For example, to estimate sulphur emissions from fossil fuel combustion the sulphur content of the fuels is needed, for certain sources with emissions control devices the efficiency of these devices is needed.

3.1. International programs

Researchers compiling national inventories for their own country usually have access to information that may not be available to others; they also have more detailed knowledge of the types of processes and operating conditions which allows the use of nation-specific emission factors or adjustment of literature values. Generally, these inventories estimate yearly emissions at the national, or for very large countries, at the level of geographic subdivisions (states, provinces, etc.). National or regional inventories may also be able to apply greater geographic resolution to sources, particularly large stationary and road and non-road mobile sources.

Researchers compiling regional or global inventories can either a) gather the national emissions estimates in the region of interest or b) estimate emissions directly using published information. To compile inventories by bringing together national estimates, the information received must be checked for transparency, consistency, completeness, comparability, and accuracy (Tarrasón and Schaug, 1999). Examples of programs that rely on national submissions to build regional or global inventories include the Co-operative Programme for Monitoring and Evaluation of the Convention on Long Range Transboundary of Air Pollutants in Europe (CLRTAP) (see section 5) and the Intergovernmental Panel for Climate Change (IPCC) (Houghton et al.,1997; Moran and Salt, 1996). Collaborations have been set up between groups concerned with gathering emissions information such as EMEP, the United Nations Economic Commission for Europe (UNECE, 1997), the United Nations Framework Convention on Climate Change (UNFCCC, 2000) and unified reporting requirements have been developed to minimize the work of the national participants and to create consistent emissions estimates for the work of these groups (Houghton et al., 1997; Moran and Salt, 1996). Step-by-step guidelines and workbooks have also been developed to help in the compilation of the required information.

In June 1985, the European Council of Ministers defined a program for gathering, coordinating, and ensuring consistency of information on the state of the environment and natural resources in the European Community. This program was called CORINE (COoRdination d'INformation Environnementale), and one of its component projects is CORINAIR (CORINe AIR emissions inventory). This program is now run by the

European Environment Agency (EEA). A prototype inventory was developed for 1985, CORINAIR85, which included a new nomenclature for source types, classification of emissions as large point sources and area sources, and especially developed software for data input and the calculation of emissions. Based on the experience gained in compiling CORINAIR85 and in collaboration with UNECE and the Organisation for Economic Cooperation and Development (OECD), the next phase of the project, CORINAIR90, has been defined (Bouscaren, 1992). In 1996 CORINAIR90 provided a complete, consistent, and transparent air pollutant emission inventory for Europe for 1990. New source sector splits have been defined (SNAP90), the list of pollutants and large point sources to be included has been expanded, and the availability of the CORINAIR software system has been extended to 30 countries in Europe. The program was taken over by the EEA in 1997, and the new source sector split was prepared in 1997 (SNAP97) which has subsequently been used in the CLRTAP/EMEP inventory programme until a new nomenclature was adopted in 2002. The joint EMEP/CORINAIR Emission Inventory Guidebook work continues, and the currently third edition is available on http://reports.eea.eu.int/technical_report_2001_3/en.

The Global Emissions Inventory Activity (GEIA), a subgroup of the International Global Atmospheric Chemistry Programme (IGAC) (Galbally, 1989), is composed of international groups of scientists attempting to establish inventories for a number of trace species, with recognized accuracy and enough spatial, temporal, and species resolution to serve as standard inventories for the international community of atmospheric scientists (Benkovitz and Graedel, 1992). In the initial compilation of the GEIA inventories of SO_2 and NO_x emissions from anthropogenic sources, a "hybrid technique" was used.

First a "default" global inventory was selected which included emissions estimates derived using a unified methodology; then national or regional emissions estimates received from cooperating researchers were studied and, if appropriate, their data were substituted for those in the default inventory (Benkovitz et al., 1996). An in-depth study of all the data was done, and differences and caveats were included in the accompanying documentation. Figure 1 presents a summary of the data used to develop the GEIA SO_2 and NO_x inventories for ca. 1985.

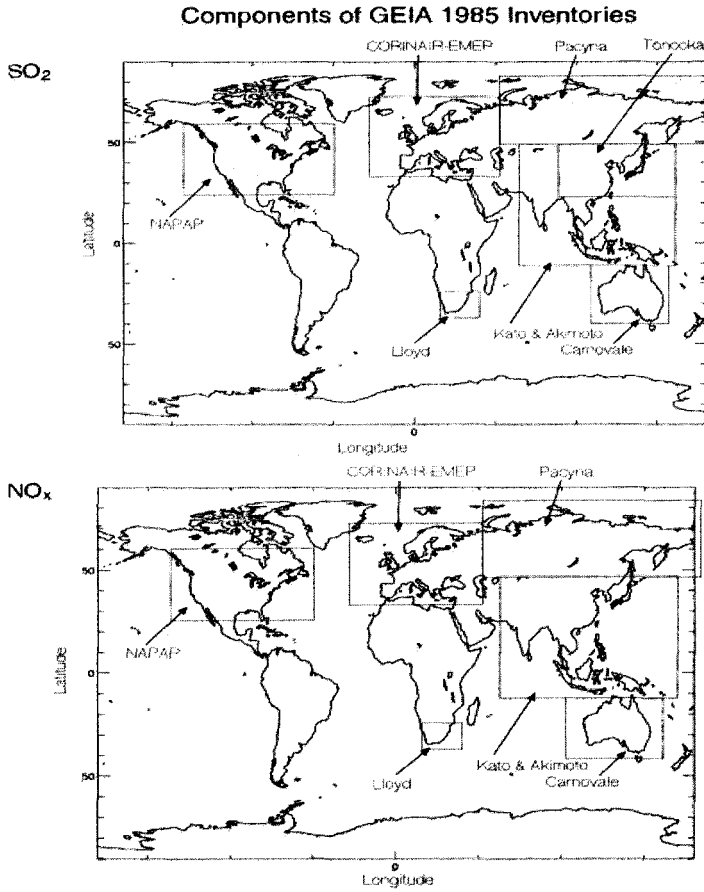


Figure 1. Regional inventories overlaid on the default global inventories of SO_2 (top panel) and NO_x.(bottom panel) for the GEIA 1985 inventories. CORINAIR, EMEP described in text. NAPAP=National Acid Precipitation Assessment Program, USA. H. Akimoto, University of Tokyo, Japan. F. Carnovale, Coffey Partners International PTY Ltd., Australia. N. Kato, National Institute of Science and Technology Policy, Japan. S.M. Lloyd, South African Department of National Health and Population Development, Pretoria. J. Pacyna, Norwegian Institute for Air Research, Kjeller. Y. Tonooka, Institute for Behavioral Sciences, Tokyo. From *Benkovitz et al, 1996.*

3.2. Direct development of inventories

To directly estimate regional or global industrial emissions, published information on activity rates, emission factors, and other pertinent parameters is needed. Examples of inventories compiled using this approach include the Emission Database for Global Atmospheric Research (EDGAR) (see section 5.1) (Olivier et al., 1999a), a set of global emissions inventories of greenhouse gases and ozone-depleting substances for all anthropogenic and most biogenic sources on a per country basis, the Regional Air Pollution Information and Simulation Model (RAINS) Asia (Arndt et al., 1997), a set of SO_2 emissions data for Asia (Foell et al., 1995), and the global CO_2 emissions compiled by Marland et al. (1994, 2002). In general, the activity rates are derived from data compiled by multi-national organizations. The two major sources of statistics on energy production, use, and trade are the International Energy Agency (IEA, 2002a,b,c) and the United Nations (UN 2000, UN 2002). Other sources of activity data for specific sectors include, but are not limited to the World Energy Council (1998), the World Resources Institute (2000), the World Bank (The World Bank Group, 2000), the International Monetary Fund (International Monetary Fund Staff, 2000), the Food and Agriculture Organization of the United Nations (FAO, 2000), the US Geological Survey (USGS, 2002) and the Motor Vehicle Manufacturers Association of the United States (1998).

These compilations are usually not independent data sets because they are based on some of the same sources for national data; the published numbers are the result of slightly different questionnaires and different analysis by the respective offices and are also reported for somewhat different categories. When using any of these sources of activity rates, the data must be carefully checked for completeness and homogeneity to avoid either double counting or dropping emissions.

In general non-road mobile sources (locomotives, construction equipment, etc.) have been less well characterized, primarily because of uncertainties in the locations of activity and in the activity levels. For example, surrogates like population may not identify the location of large construction projects, and construction or logging equipment may be idle much of the time. In the case of international shipping, these uncertainties were compounded by limited information about the emissions factors assigned to marine engines.

The U.S. Environmental Protection Agency has developed and maintains a compilation of emission factors applicable to U.S. sources (U.S. Environmental Protection Agency, 1999). Canada has also developed emission factors applicable to their sources (Johnson et al., 1991). The IPCC (Houghton et al., 1997) and the United Nations Framework Convention on Climate Change (UNFCCC) (United Nations Framework Convention on Climate Change, 2000) have developed extensive guidelines, which include step by step methodologies and emission factors to be used in estimating and reporting emissions. In addition, some investigators either adapt the US or Canadian emission factors or perform literature searches for more appropriate values or for experimental data from which to develop their estimates; for examples see Kato and Akimoto (1992) and Arndt et al. (1997).

A vivid example of the impact that small differences in input data can have on emissions estimates is given by Marland et al. (1999), where the annual-by-country CO_2 emissions values in the Marland et al. inventory were compared with those in the EDGAR 2.0 inventory. Marland et al. rely mainly on statistics gathered by the UN, while EDGAR relies mainly on statistics gathered by the IEA supplemented by UN statistics when needed. After trying to account for the different sectors and emission factors included in each inventory, results presented in Figure 2 show that most of the emissions estimates cluster around the 1:1 line.

The mean of all country differences between the two inventories is about 1%, but the fractional differences tend to be larger for countries with smaller emissions, probably due to larger uncertainties in the activity rate information. However, the relative difference between the two estimates for US emissions is only 0.9%, but the absolute difference is larger than the total emissions from 147 of the 195 countries included in the analysis. For the former Soviet Union, the relative difference is about 8.1%, but the absolute difference exceeds the total emissions from all but the 14 largest emitting countries.

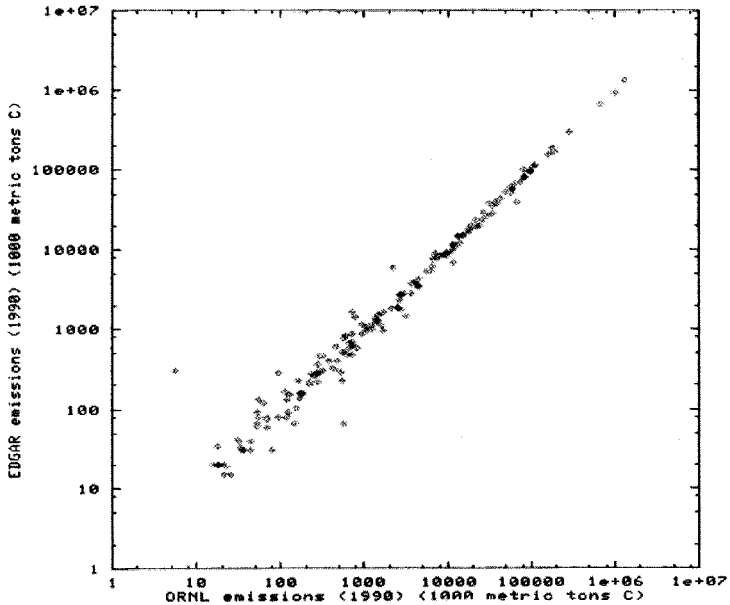


Figure 2. Correlation of countries' total emissions as calculated by EDGAR and ORNL. (from *Marland et al, 1999).*

Direct measurements of emissions can be carried out using continuous emissions monitoring (CEM) techniques; this methodology produces the most accurate emissions estimates for the sources being monitored at the temporal resolution of the measurements. In the United States, these measurements are currently in use mainly at large stationary sources, which are under strict guidelines for emissions control, such as power plants operating under state implementation plans.

4. SECTORAL, TEMPORAL, SPATIAL AND SPECIES RESOLUTION

For scientific studies and increasingly for management and policy, perspective emission inventories are needed by source sector at more detailed temporal, spatial, and species resolution. As the main driving force for the compilation of national inventories is the need to regulate sources, emissions by source sectors are usually available in these inventories.

Usually, activity rate compilations are also developed by source sector. Unfortunately, the sectoral definitions are far from being uniform; they vary from the very detailed descriptions used by the US Environmental Protection Agency (source classification codes), the Canadian adaptation of this classification scheme, and CORINAIR SNAP97 to those with only a very limited number or no sectors. The EDGAR inventory and the 1990 SO_2 and NO_x inventories of anthropogenic emissions developed at the Canadian Global Interpretation Centre (CGEIC) (Van Heyst et al., 1999) have adopted sector classifications that can address the needs of regional to global studies. As an example, Table 1 presents the source classification used by the CGEIC inventories. Except for CEM measured emissions, there is a lack of information on emissions at finer temporal, spatial, and species resolutions; therefore surrogate methods are used to bring the inventory information to the desired resolutions where possible.

Main Source	**Sector Division**	**Source Type**
Power generation	Power generation	Elevated point [a]
Fuel use & combustion	Industry (including other transformation sectors)	Low level point [b]
	Residential, commercial, other	Area [c]
	Incineration	Area
Transportation	Road	Mobile
	Non-road (*e.g.* rail)	Mobile
	Air (below 1 km)	Mobile
	International shipping	Mobile
Industrial processes	Iron & steel (excludes coke ovens and blast furnaces)	Elevated point
	Non-ferro	Elevated point
	Chemicals	Low level point
	Pulp & paper	Elevated point
	Other	Low level point
Land use	Biomass burning	Area

Table 1: Sector Description for the Canadian Global Interpretation Centre (CGEIC). 1990 Global Inventory of SO_2 and NO_x Emissions from Anthropogenic Sources
[a] Stationary source with emissions discharge point at an altitude of 100 m or higher.
[b] Stationary source with emissions discharge point at an altitude of less than 100 m.
[c] A surface-level stationary source with small emissions. An aggregation of these sources in an area can have significant emissions.

The exact location (longitude, latitude) for most of the large stationary point sources such as power plants, smelters, etc. is currently available; this allows precise geographic assignment of their emissions. However, additional information needed to properly assign these emissions in the vertical, such as stack height, flow rate, temperature, etc. is rarely available. This additional information becomes critical to models where a more exact representation of plume dispersion is needed, such as the plume-in-grid (PinG) section of the community multiscale air quality modelling system (Byun and Ching, 1999). The minimum information needed to estimate the vertical release height of large stationary point source emissions is the stack height; however, with only this information accurate plume dispersion cannot be represented.

The inventories compiled for the National Acid Precipitation Program (NAPAP) were among the first to address the conversion of emissions data to the finer spatial, temporal, and species resolution required by Chemical Transport Models (CTMs, Saeger et al., 1989; Wagner et al., 1986). This work developed temporal, spatial, and species allocation factors for emissions in the United States and Canada. Temporal allocation factors were based on surrogate information such as average heating degree days, continuous traffic counts from the US Department of Transportation, operating schedules for power plants, etc. Twelve temporal categories were achieved: weekday, Saturday, and Sunday for each of the four seasons. The location of all major stationary sources was known, so the emissions were assigned to the corresponding grid cell. The spatial allocation factors for non-stationary sources were developed using the appropriate gridded surrogate information such as population, housing, land use types, etc. Speciation factors for NO_x used were those recommended in AP-42 (US Environmental Protection Agency, 1985); speciation factors for total suspended particulates (TSP), and total hydrocarbons (THC) were based on the Air Emissions Species Manual (Shareef and Bravo, 1993ab) developed for the US Environmental Protection Agency.

The EUROTRAC-2 (European Experiment on Transport and Transformation of Environmentally Relevant Trace Constituents) subproject on the Generation and Evaluation of Emission data (GENEMIS, http://www.ier.uni-stuttgart.de/genemis) has investigated and improved the methodology for the temporal, spatial and substance resolution of air pollutant emissions in Europe (Friedrich et al., 2000, 2002). The pollutants

covered include anthropogenic and biogenic precursors of ozone, aerosols and acidifying substances. As methods for developing emission inventories for CO, SO_2 and NO_x are more advanced and the resultant uncertainties in their emission estimates are lower than those for VOC, PM and NH_3, work within GENEMIS largely focussed on the latter pollutants.

General aim of GENEMIS was to support the generation of validated emission data, that could be used for the development of air pollution abatement strategies in Europe. This included improvement of methods, models and emission factors for the generation of emission data. A second focus was the assessment of the accuracy and the validation of emission data and finally, the development and improvement of tools to generate emission data for atmospheric models (CTMs). GENEMIS has improved knowledge about uncertainties of emission data by carrying out or analysing results from whole city, tunnel and open road experiments and statistical analyses of uncertainties. Uncertainties are still large, this has to be taken into account when interpreting results of atmospheric models.

A number of models to set up emission inventories for street canyons, for urban areas and for regions have been developed and improved. A large number of regional and urban emission data sets have been generated and provided to groups applying atmospheric models.

Some of the surrogate data needed to give emissions inventories finer resolution are not always developed on a gridded basis; for example, population data are based on geopolitical division, transportation data are "line" sources, etc. For other data sets, such as satellite information, the "native" grid of the data may not exactly match that of the atmospheric models. The conversion of these data to gridded format (or regridding to a new grid definition) adds another source of uncertainty to the emissions data, so care must be exercised when developing and applying the gridded surrogate data. For example, in his work with the 1990 population counts Li (1996) had to take into consideration problems with multiple geographic entities (including ocean areas) within one grid cell and how this affects the distribution of both the population and ultimately the emissions.

International shipping (A modern "fleet of ships does not so much make use of the sea as exploit a highway", Joseph Conrad, The Mirror of the Sea, 1906) provides another example of using unique surrogate data to characterize the geographic domain of a sector's emissions. While ships operate along well-known shipping lanes, these "water highways" are not

mapped directly and they vary by season and with the weather. In order to develop gridded emissions inventories for NO_x and SO_x from shipping, a surrogate for vessel traffic density by location was derived from atmospheric and ocean observations reported by ships participating in the worldwide weather watch. Ship observations in each gridded location are averaged and compiled by month in the Comprehensive Atmosphere Ocean Database (COADS), used by scientists and modellers (Woodruff, 1993). Using the number of shipboard observations that were averaged in each grid cell for one attribute (e.g., air temperature), the implied traffic density for commercial shipping can be obtained for each month of the year; results are presented in Figure 3.

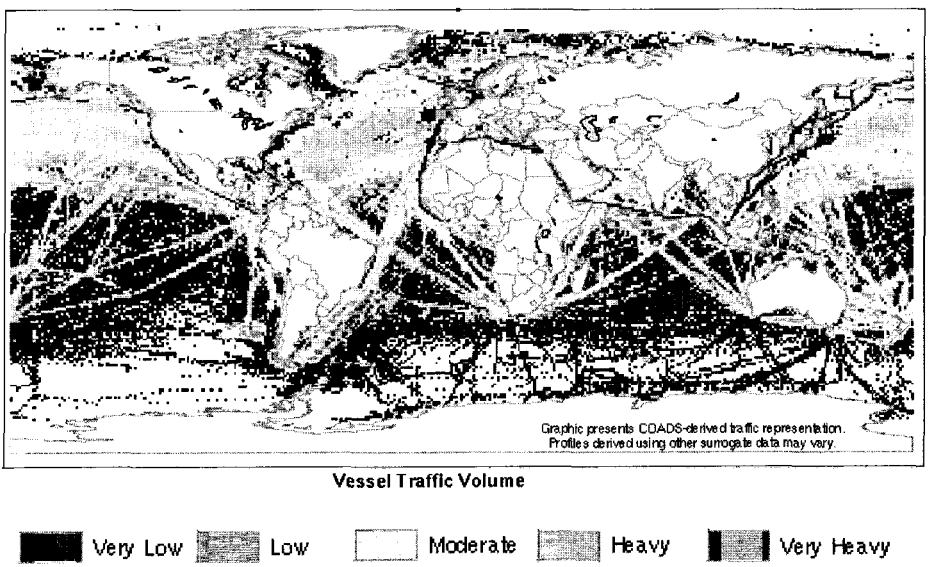


Figure 3 (see plate 3). International ship traffic for 1990 (adapted from Corbett et al., 1999 and Skjølsvik et al. 2000)

The accuracy of the resulting ship traffic profiles depends upon two fundamental assumptions: 1) a statistically significant population of ships reports to COADS; and 2) that sample of ships is representative of the international fleet overall. However, some 16% of the world cargo fleet reports to COADS, and comparison with regional inventories using more direct bottom-up traffic profiles has verified the accuracy of this approach

(Corbett, 1997; Corbett et al., 1999). Some researchers are beginning to compare the COADS-derived ship profiles with other surrogates, such as the Automated Mutual Assistance Vessel Rescue System (AMVER), to evaluate relative merits in terms of completeness, transparency, consistency, comparability and accuracy. To complete the emissions inventory, activity level for ship engine systems and emissions factors are applied as in other inventories, discussed above.

The surrogate approach has desirable features for global inventories. It directly reveals global resolution and is easily updated for different years, updated activity information, or better emissions factors. It suffers from some of the same limitations as other sectoral inventories. Chief among these is the limited resolution, which results in an increasing loss in confidence if modellers try to zoom in beyond a large region to only a few cells.

The difficulty is in finding appropriate surrogates that can be verified and applied to different years. In the case of shipping, the weather data appears to be robust over the past several decades. The data might not be a good record before 1960 because of changes in fleets or their technologies. Related to this is the challenge of reconciling port-level or regional bottom up inventories with the globally derived data. However, the agreement in many cases appears to be very good and differences are equally attributable to uncertainties in the port- or regional-scale and global-scale inventories.

5. EXAMPLES OF ANTHROPOGENIC EMISSIONS INVENTORIES

5.1. The EDGAR 3 global inventories

5.1.1. Method

The EDGAR (Emission Database for Global Atmospheric Research) project is a comprehensive task carried out jointly by the National Institute for Public Health and the Environment (RIVM) and the Netherlands Organization for Applied Scientific Research (TNO) (Olivier et al., 1996,

1999a; Olivier and Berdowski, 2001) (http://www.rivm.nl/env/int/coredata/edgar). This set of inventories combines information on all different emission sources, and it has been used over the past few years as a reference database for many applications. The work is linked into and part of the Global Emissions Inventory Activity (GEIA) of IGBP/IGAC (Bouwman et al., 1995, 1997; Olivier et al., 1996, 1999b; Olivier and Berdowski, 2001). The initial version of the full data set, EDGAR 2.0, provides global annual anthropogenic emissions for 1990 of greenhouse gases CO_2, CH_4 and N_2O and of precursor gases CO, NO_x, NMVOC and SO_2, on a regional basis and on a $1^o x 1^o$ grid. Similar inventories were compiled for a number of CFCs, halons, methyl bromide, and methyl chloroform. In the follow-up project the database was extensively validated and an uncertainty analysis was carried out. Most of the applications of EDGAR 2.0 over the last few of years are in model studies, but EDGAR data are also extensively used for policy applications for which emissions data on country level were calculated with the EDGAR information system. EDGAR datasets have also been used in IPCC Assessments, both on source strengths and on spatial distribution of emissions in the development of emission scenarios (IPCC, 2001).

The database has been updated to EDGAR 3.2, which includes an update and extension from 1990 to 1995 for all gases and extended time series for direct greenhouse gases to 1970-1995, as well as the new 'Kyoto' greenhouse gases HFCs, PFCs, SF_6 (Olivier et al., 2001). Selected time profiles for the seasonality of anthropogenic sources have also been identified. For the update of version 2.0 to version 3.2, the following principles were followed:

- *Activity data*: updated by including relevant statistics for the period 1970-1995, after checking for possible changes of source categories; this implies the inclusion of the 'new' countries, e.g. for the former SU.

- *Emission factors*: only to be changed for 1990 if validation showed major discrepancies; only to be changed for 1995 compared to 1990 if there are concrete indications that major changes have occurred that cannot be neglected; the same holds for factors for 1970, in particular for direct greenhouse gases.

- *Grid maps*: only to be updated if maps available of better quality or better applicability.

The EDGAR 3.2 data set includes new types of emissions, such as unintentional coal fires at shallow coal deposits, which appeared to be considerable for China. The Gulf war oil fires in Kuwait in 1991 have been included as separate source. Recognizing the importance of emissions related to biomass burning temperate vegetation fires have been added as an emission source based on the UN/ECE forest fire statistics for 1987 to 1997 (UN/ECE-FAO, 1996; UN/ECE-FAO, 1998; see also Chapter 3). Wastewater treatment and domestic waste combustion were also added as sources contributing substantially to CH_4 emissions.

Several significant changes are obtained when compared with the previous EDGAR 2.0 inventory. For example, agricultural waste burning emissions have decreased substantially, in particular for CO, due to lower fractions assumed to be burned and a substantial decrease in the CO emission factor. NMVOC emissions from domestic waste burning and from 'miscellaneous' industrial non-combustion processes have also decreased significantly after a re-analysis of the source data. The emissions from fossil fuel fires are now taken into account, which greatly increases fuel-related emissions in China, and NO_x from international shipping has also increased substantially due to an update of the emission factors. The spatial distribution of sources allocated with the population maps has noticeably changed too due to the introduction of another base map from Li (1996) and applying urban and rural maps where appropriate (Olivier et al., 2001).

The inventory is updated regularly due to changing emission factors, and because international statistics of activity data for the most recent years tend to vary during the first few of years after initial compilation. It should also be noted that data for the former Soviet Union have become rather weak due to inconsistencies between the sum of the new countries and the 1990 data for the former SU (Olivier et al., 2001).

5.1.2. Emissions

As it is the case with all global or regional inventories, the uncertainty in the emission inventories may be substantial, due to 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., 1996, 1999a, 2001). The methods used are comparable with IPCC methodologies (IPCC (1996;

2001) which are based on international information sources, and global totals comply with budgets used in atmospheric studies. At regional and global levels part of the uncertainty caused by limited precision of national activity data may be reduced by aggregation to higher spatial levels. This is, however, not true for the emission factors used to construct the emission inventories, because these are often based on literature values in which sets of emission factors were compiled and reviewed (Olivier and Peters, 2002). Therefore the dataset could contain some bias, although resulting global or regional emissions are generally in line with other estimates and with atmospheric budgets.

5.1.2.1. Methane (CH_4)

Within the framework of EDGAR 3.2 a special effort was made to compile a new global dataset for anthropogenic CH_4 emissions, aiming at providing reference data on a per country basis and at providing emission trends for the period 1970-1995. The dataset is based not only on international statistics from organizations such as IEA, FAO and UNDP, but has been supplemented with more detailed activity data where relevant for emission calculations, e.g. surface and underground mining, different ecology types of rice cultivation, etc. The CH_4 emission factors used in EDGAR 3.2 are mostly based on the IPCC 'Tier 1' default values (i.e. for the simplest standard emission calculation method), in particular for the agricultural sector (Houghton et al., 1997). The emission factors are also region-specific and time-dependent for major sources where a large degree of uniformity across time and space was not considered likely. In particular, aggregated emission factors varying in time were used for coal production, rice production, and landfills. For example, coal production, rice production, surface and underground mining, and different ecology types of rice cultivation have very different emission factors, which should be accounted for when the mix of these types changes over time. Global total anthropogenic emissions of CH_4 have been estimated at about 250 Tg in 1970 and at about 300 Tg in 1990, staying at approximately this level until 1995.

Table 2 summarizes the CH_4 emissions by region and by major source category. At a 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, the analysis by Doorn et al. (1997, 1999) concludes that landfills, domestic and industrial wastewater disposal (latrines, septic tanks, open sewers, and wastewater treatment plants) appear to contribute about the same to global methane emissions. Within the fossil fuel category coal production and gas transmission are the largest sources. The regions contributing most to the global total in 1995 are East Asia with 16% followed by South Asia, USA, Latin America and the former Soviet Union (SU), each contributing 12% to 14%. In the 25-year period 1970-1995, global emissions of CH_4 have increased by about 20%. In the 1980s the growth was about 10%, predominantly due to the strong increase in gas production and transmission in the former SU. Enteric fermentation by ruminants and wastewater disposal, particularly in less developed regions, also contributed to this growth.

The declining economy of the former SU countries in the early 1990s had a large impact on the global trend in CH_4 emissions: coal and gas production emissions dropped substantially between 1990 and 1995. It should be stressed, however, that statistics for this region are rather uncertain for this period.

Table 2: Sources and regional contribution of emissions of CH_4 in 1995 (Tg). Source: EDGAR 3.2

	Total	Canada	USA	OECD Europe	Oceania	Japan	Eastern Europe	Former SU	Latin America	Africa	Middle East	South Asia	East Asia	South East Asia
Fossil fuel	91.1	2.1	21.5	4.3	1.3	0.8	4.7	24.0	3.4	3.5	6.0	1.9	13.5	4.0
Biofuel	13.9	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
Indust. processes	0.8	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
Agriculture	134.1	1.0	7.5	7.7	4.2	0.4	2.2	7.8	21.8	14.5	2.2	28.2	23.9	12.7
Biomass burning	6.5	1.5	0.2	0.1	0.1	0.0	0.0	0.1	2.0	1.0	0.0	0.1	0.0	1.3
Waste handling	55.7	1.2	10.3	5.0	0.6	1.6	1.2	3.7	7.2	4.1	1.5	8.1	7.6	3.5
Total	**301.9**	**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**

Within OECD Europe, CH_4 emissions from coal production have decreased substantially as a result of the policies in Germany and the United Kingdom to reduce the amount of domestic coal production. This compensated for the increasing emissions from the waste handling sector, in particular in Asia, and caused the total global emissions of methane to stabilize during the early 1990s.

5.1.2.2. Carbon Monoxide (CO) and Nitrogen Oxides (NO_x)

In EDGAR 3.2 the anthropogenic emissions of CO and NO_x have been estimated at about 860 Tg CO and 110 Tg NO_2 in 1995. The global distributions of the emissions of NO_x and CO are presented in Figure 4.

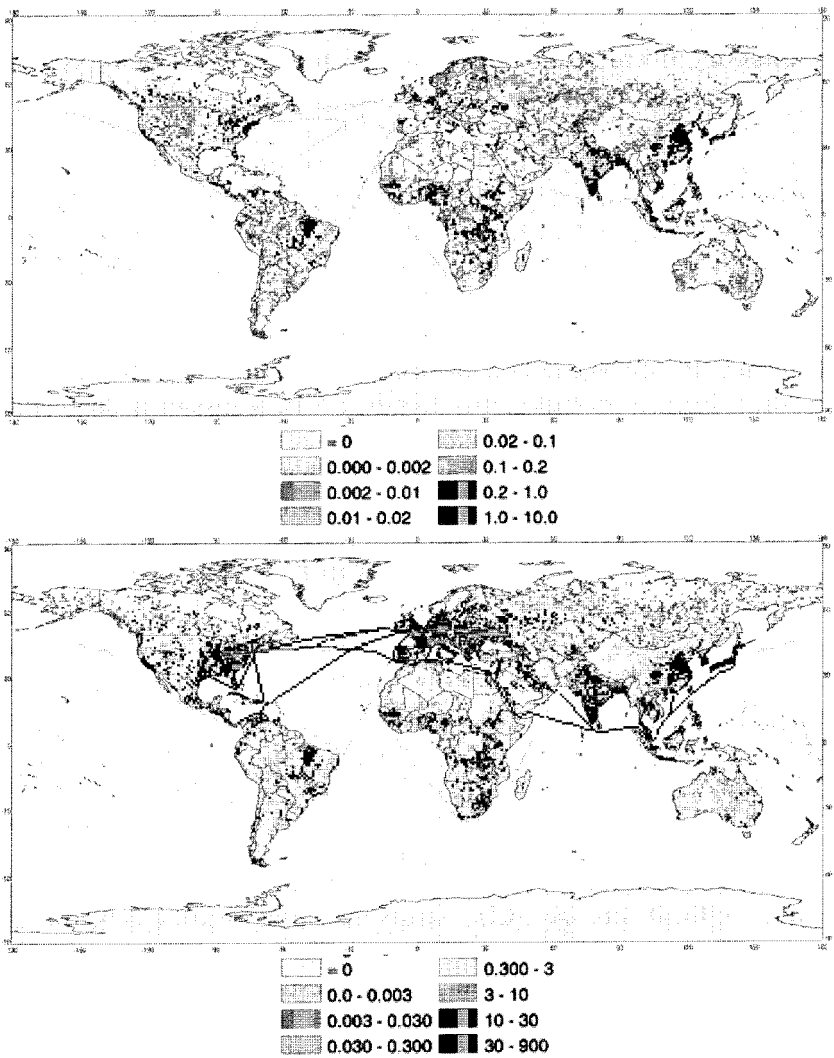


Figure 4 (see plate 4): Global distribution of CO (top, in Tg CO) and NO_x (bottom, in Gg NO_x) anthropogenic emissions in 1995. Source: EDGAR 3.2

Since 1990 total global anthropogenic emissions of these two species remained approximately constant, but the distribution of emissions across regions has changed substantially in this 5 year period: For example, in the former SU CO emissions have decreased by 45% or 35 Tg and NO_x emissions 37% or 6 Tg NO_2 due to the economic decline after the breakup of the union; in OECD Europe CO emissions decreased by 5% or 5 Tg and NO_x by 16% or 3 Tg as a result of emission control policies. The large emissions of CO in 1995 (45 Tg) are a result of the large extent of accidental vegetation fires in 1995. NO_x emissions increased significantly in Asia, by 25% to 45% (5 Tg in East Asia). Globally only the smaller NO_x sources show large changes; the largest sources (road transport, power generation and industrial combustion) remained almost constant in the early '90s, as shown in Tables 3 and 4.

Table 3: Sources and regional contribution of emissions of NO_x in 1995 (Tg NO_2). Source: EDGAR 3.2

	Total	Canada	USA	OECD Europe	Oceania	Japan	Eastern Europe	Former SU	Latin America	Africa	Middle East	South Asia	East Asia	South East Asia
Fossil fuel	83.5	1.9	19.8	13.0	1.5	2.9	2.4	9.1	5.7	3.2	4.5	4.1	12.2	3.1
Biofuel	7.7	0.0	0.5	0.1	0.0	0.0	0.0	0.2	0.5	1.5	0.1	2.3	1.5	0.9
Indust. processes	6.1	0.1	0.5	0.9	0.0	0.4	0.2	0.4	0.4	0.2	0.4	0.3	2.0	0.3
Agriculture	0.7	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.1
Biomass burning	13.0	1.8	0.2	0.1	0.7	0.0	0.0	0.1	3.3	6.0	0.0	0.1	0.1	0.7
Waste handling	0.1	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
Total	***111.3***	***3.8***	***21.0***	***14.2***	***2.3***	***3.4***	***2.8***	***9.9***	***10.1***	***11.1***	***5.1***	***6.7***	***15.9***	***5.1***

Over the five-year period 1990-1995 the distribution of CO emissions across sources categories has changed, but less than the regional distribution. For example, residential biofuel emissions increased by 7% or 15 Tg, road transport emissions increased by 6% or 10 Tg, and temperate forest fires increased by 25 Tg. Emissions from residential fossil fuel combustion decreased by 30% or 15 Tg and deforestation emissions decreased by 10% or 10 Tg.

Table 4: Sources and regional contribution of emissions of CO in 1995 (Tg CO). Source: EDGAR 3.2

	Total	Canada	USA	OECD Europe	Oceania	Japan	Eastern Europe	Former SU	Latin America	Africa	Middle East	South Asia	East Asia	South East Asia
Fossil fuel	278.3	6.0	76.7	36.2	4.2	6.9	8.8	26.9	27.2	11.2	16.6	5.1	42.6	10.0
Biofuel	231.6	0.4	5.6	2.1	0.6	0.1	1.2	5.8	9.6	56.3	2.7	68.4	49.2	29.6
Indust. processes	31.8	0.4	2.4	5.8	0.4	4.4	1.6	5.0	1.8	0.4	0.4	1.0	8.0	0.2
Agriculture	16.4	0.2	1.0	0.8	0.6	0.1	1.3	1.9	2.9	2.2	2.2	0.6	0.4	2.2
Biomass burning	298.9	45.7	4.9	2.8	12.8	0.1	0.0	2.3	83.3	114.4	0.4	2.2	1.4	28.5
Waste handling	3.8	0.1	1.3	0.2	0.1	0.5	0.1	0.2	0.3	0.2	0.1	0.3	0.4	0.1
Total	**860.8**	**52.7**	**91.9**	**47.9**	**18.7**	**12.0**	**13.1**	**42.2**	**125.1**	**184.8**	**22.3**	**77.6**	**101.9**	**70.7**

5.1.2.3. Non-Methane volatile organic compounds

In 1995 total global anthropogenic emissions of non-methane volatile organic compounds (NMVOCs) have been estimated at about 160 Tg (Table 5); this corresponds to an increase of about 5 Tg since 1990. The largest changes occurred in the former SU, where total emissions decreased by 40%; oil production decreasing by 200% and road transport by 70%, or 2 Tg each.. In contrast, road transport emissions in East Asia increased by 49% and in the USA by 10%, approximately 1 Tg each. Emissions from oil production in OECD Europe increased by 30% and in the Middle East by 10%, approximately 1 Tg each.

Table 5: Sources and regional contribution of emissions of NMVOC in 1995 (Tg). Source: EDGAR 3.2

	Total	Canada	USA	OECD Europe	Oceania	Japan	Eastern Europe	Former SU	Latin America	Africa	Middle East	South Asia	East Asia	South East Asia
Fossil fuel	79.0	2.4	10.7	10.1	1.4	3.0	1.4	13.5	8.4	4.8	11.5	2.0	5.5	4.5
Biofuel	28.0	0.0	0.8	0.3	0.1	0.0	0.1	0.7	1.4	6.9	0.3	8.1	5.9	3.5
Indust. processes	25.4	0.5	6.6	5.4	0.3	2.6	0.9	2.6	1.6	0.8	0.6	0.8	1.9	0.9
Agriculture	2.0	0.0	0.1	0.1	0.1	0.0	0.2	0.2	0.3	0.3	0.3	0.1	0.0	0.3
Biomass burning	22.4	6.1	0.7	0.4	0.9	0.0	0.0	0.3	4.9	7.4	0.0	0.1	0.1	1.5
Waste handling	2.7	0.1	0.7	0.5	0.0	0.3	0.1	0.3	0.2	0.1	0.1	0.1	0.2	0.1
Total	**159.6**	**9.2**	**19.5**	**16.8**	**2.8**	**5.9**	**2.7**	**17.6**	**16.8**	**20.1**	**12.7**	**11.1**	**13.7**	**10.8**

5.1.2.4. Sulfur Dioxide (SO_2)

In EDGAR 3.2 the total global anthropogenic emissions of SO_2 for 1990 have been estimated at about 155 Tg, with a slowly decreasing trend in subsequent years (Table 6). The decrease is mainly due to control measures implemented in OECD Europe and the USA and to the declining economy of the former SU countries. Decreases in power generation and industrial combustion in the former SU countries more than compensated for the high growth of SO_2 emissions in Asia, which showed an average 5-year growth rate of about 30% in the 1990-1995 timeframe.

Table 6: Sources and regional contribution of emissions of SO_2 in 1995 (Tg SO_2). Source: EDGAR 3.2

	Total	Canada	USA	OECD Europe	Oceania	Japan	Eastern Europe	Former SU	Latin America	Africa	Middle East	South Asia	East Asia	South East Asia
Fossil fuel	111.2	2.2	17.1	11.4	1.0	1.5	8.9	13.0	4.9	3.8	5.1	5.4	34.0	3.0
Biofuel	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.6	0.0	1.5	0.5	0.1
Indust. processes	25.0	0.4	1.0	5.0	0.5	0.6	1.6	3.0	4.4	1.3	0.5	0.5	5.7	0.5
Agriculture	0.2	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
Biomass burning	2.5	0.2	0.0	0.0	0.1	0.0	0.0	0.0	0.7	1.1	0.0	0.0	0.0	0.2
Waste handling	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
Total	**141.9**	**2.8**	**18.1**	**16.5**	**1.7**	**2.2**	**10.5**	**16.0**	**10.1**	**6.9**	**5.7**	**7.5**	**40.2**	**3.8**

5.2. The EMEP regional inventory

The EMEP inventories consist of emission data officially reported annually by the 49 Parties to the Convention of Long Range Transboundary Air Pollution (CLRTAP) (Vestreng and Klein, 2002, and http://www.unece.org/env/lrtap/). These inventories include emissions from 1980 to 2000, and projections for 2010 and 2020, for SO_2, NO_x, ammonia (NH_3), NMVOC, CO, Particulate Matter (Total Suspended Particulates, TSP; Particulate Matter with diameter < 2.5 μm, $PM_{2.5}$; Particulate Matter with diameter < 10 μm, PM_{10}; all by mass), selected heavy metals (HMs), and Persistent Organic Pollutants (POPs). National totals, data by sectors, and gridded data are available from WebDab, which is the web version of the UNECE/EMEP emission database, at the EMEP website: http://webdab.emep.int/ and documented in the EMEP Emission Report (Vestreng and Klein, 2002). Wherever there are spatial or temporal gaps in the inventory expert estimates of emissions are developed and included in the information available to the public. The EMEP inventory is updated during the spring each year. The gridded emission data are available in 50 x 50 km, 150 x 150 km, and 1° x 1° grid resolutions.

To assist the CLRTAP countries in their work of estimating and submitting transparent, consistent, comparable, and accurate emission estimates, an atmospheric emission inventory guidebook has been made available on the internet at http://reports.eea.eu.int/technical_report_2001_3. It is the responsibility of the countries to assure the accuracy of the reported emissions. To serve as input to scientific studies within and outside the EMEP community the data still need to be scrutinized and in some cases replaced by or completed with expert estimates. Gaps in total

national emissions are filled by data from documented sources like the GEIA inventories, the International Institute for Applied Systems Analysis (IIASA) data, or by linear interpolation. Sector emissions are completed by applying an average sector distribution developed for Europe based on reported data available in the UNECE/EMEP database. The spatial distribution is developed based on knowledge about point source and population distribution. Work is ongoing within EMEP to improve and document methods used to create expert estimates

Table 7: EMEP national total emissions for 1995 (Gg/year). Emissions officially reported by the Party to the Convention on LRTAP are displayed with no background. Values in grey shaded cells are interpolated and/or drawn from documented sources. From Vestreng and Klein, 2002 (NO_x as NO_2; NA: non available).

Area/Species	SO_2	NO_x	NH_3	NMVOC	CO	PM2.5	PM10
Albania	72	24	32	31	84	6.13	8.21
Armenia	2.5	14.9	25	23.4	173.6	4.73	6.56
Austria	53.82	182.7	74.13	275.7	1098	27.64	46.81
Belarus	275	195	142	367	1253	38.47	62.36
Belgium	245.4	324.9	97.30	250.3	1013	57.06	84.12
Bosnia and Herzegovina	480	80	31	51	280	5.67	9.85
Bulgaria	1476	266	99	173	846	37.64	93.06
Croatia	70.4	65.7	24.9	74.1	345.8	13.74	21.03
Cyprus	41	19	4	19	67	1.76	2.96
Czech Republic	1091	412	86	286	874	57.38	125.42
Denmark	149.0	261.4	112.2	152.8	688.3	12.10	27.07
Estonia	118.5	42.06	10.97	47.5	242.3	13.69	33.27
Finland	96	258	35.2	189.0	436	20.02	30.03
France	995	1709	758	1979	8880	336.00	588.00
Georgia	20.3	26.6	97	1.5	249.5	6.99	10.03
Germany	1994	1967	635	2024	6667	217.10	335.28
Greece	528	309	85	329	1316	41.87	62.44
Hungary	705.0	190.1	77.00	150.3	761.3	27.78	60.24
Iceland	23.9	28.4	3	12.0	49.4	1.62	2.03
Ireland	161.2	115.3	119.6	105.4	304.4	12.85	22.66
Italy	1322	1768	461	2368	7755	232.27	319.31
Kazakhstan	140	76	18	76	266	NA	NA
Latvia	58.98	41.76	16.82	64.04	436.5	8.57	13.21
Lithuania	94	65	38	77	286	12.68	19.83
Luxembourg	9	21	7	16	107	2.79	5.19
Netherlands	141.4	483.5	186.2	369.6	894.0	41.42	60.90
Norway	33.57	222.7	25.99	367.8	746.6	43.09	48.98

Table 7 (Cont'd). EMEP national total emissions for 1995 (Gg/year).

Poland	2376	1120	380	769	4547	126.93	313.82
Portugal	365.6	357.8	101.7	461.6	1201	36.98	50.99
Republic of Moldova	64.06	38.2	33	61.7	192	9.83	16.36
Romania	912	319	221	638	2325	92.84	185.59
Russian Federation	2969	2570	824	2857	9945	895.71	1709.1
Slovakia	239	174	39.6	159	404	22.98	40.57
Slovenia	125	67	22	44	91	6.68	13.22
Spain	1808	1355	467	1536	3569	158.46	225.58
Sweden	68.56	309.2	61	471.5	993.6	29.74	42.05
Switzerland	33.55	120	69.2	199.4	490.9	15.48	28.22
The FYR of Macedonia	105	30.4	17	19	77	9.58	27.39
Turkey	1772	800.5	321	677.3	3987	204.43	390.67
Ukraine	1639	531.0	729	811.0	2906	281.45	608.11
United Kingdom	2363	2088	318	2054	5522	132.30	237.86
Yugoslavia	462	59	90	142	207	48.88	144.33
North Africa	413	96	235	96	336	NA	NA
Remaining Asian areas	869	212	303	212	742	NA	NA
Baltic Sea	228	352	0	8	29	NA	NA
Black Sea	57	86	0	2	8	NA	NA
Mediterranean Sea	1189	1639	0	34	139	NA	NA
North Sea	454	648	0	15	59	NA	NA
Rem. N-E Atl. Ocean	901	1266	0	25	111	NA	NA
marine emissions	742	0	0	0	0	NA	NA
Volcanic emissions	2000	0	0	0	0	NA	NA
Total EMEP	32552	2340	7533	2117	74001	NA	NA

Within EMEP, the inventories are used to check the compliance of countries with different United Nations (UN) Protocols (see http://www.unece.org/env/lrtap for details) and as input to a multitude of atmospheric models used in assessment studies.

A new set of guidelines for estimating and reporting emissions data for CLRTAP were adopted in 2002 (http://www.unece.org/env/documents/2002/eb/ge1/eb.air.ge.1.2002.7.e.pdf) The major changes include the harmonization of the definition of sectors with those of the United Nations Framework Convention on Climatic Change (UNFCCC) common reporting format, and facilitating reports of information on large point sources and activity data. Table 7 lists the areas covered by the EMEP modeling domain; and the 1995 total emissions of SO_2, NO_x, NH_3, NMVOC, CO, $PM_{2.5}$, and

PM_{10} in these areas are tabulated as an example of emission data available from WebDab.

Figure 5 presents the spatial distribution of the NO_x emissions in 50 x 50 km grid resolution. A base grid representing emissions in the year 2000 is downscaled to the year 1995. The user of WebDab can however choose any presently available year: 1980-2000, 2010 and 2020.

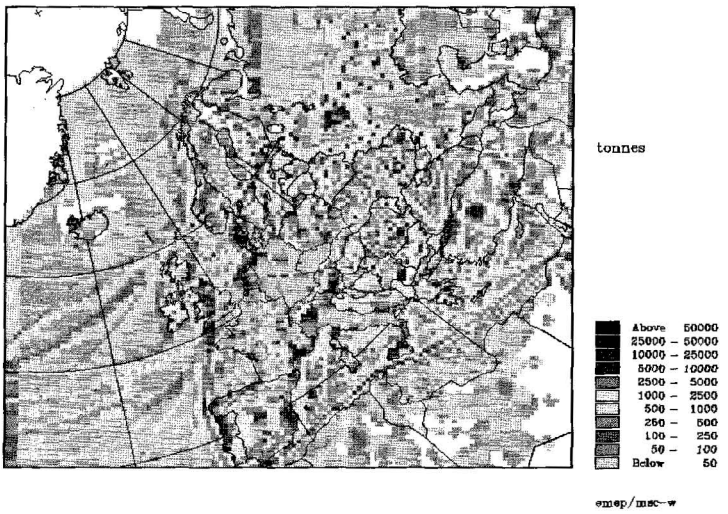


Figure 5 (see plate 5). European emissions of NO_x in 1995 at 50 km grid resolution (Mg as NO_2) (reproduced with permission of Norwegian Meteorological Institute/EMEP/MSC-W).

The comparison shown in Table 8 between the EMEP and the EDGAR3.2 emission data for NO_2 provides and excellent illustration of the point made by the Marland study of CO_2 emissions (section 3.2). While the total percentage difference between the EMEP and EDGAR3.2 data for OECD EUROPE is only 6 percent, differences up to 70 percent can be seen for individual countries. The largest differences are seen for the countries with the smallest emissions. The absolute difference in Giga Grams is larger than the emissions from 13 out of 18 countries. For the Eastern European countries, the total difference is even smaller, 3 percent, while differences for individual countries that have reported data to EMEP reach 173 percent, and almost 50 percent of the countries have emissions larger than the absolute difference.

It is interesting to note that for OECD EUROPE the EDGAR3.2 inventory in most cases underestimates emissions as compared to the countries' own estimates. For the Eastern European countries, there is a fifty-fifty split between over and under estimation while all the Former Soviet Union (SU) countries report less emissions than estimated by EDGAR. There is a large (more than 100 percent) underestimation in the reported emission data by the former SU countries relative to the EDGAR data, and the absolute difference exceeds the emissions from all the individual countries. The underestimation increases to more than 200 percent, when excluding Kazakhstan and the Russian Federation. For these two countries the EMEP estimates only consider the European part of these countries' territories, while EDGAR includes the total territory.

Table 8: Comparison between EMEP and EDGAR 3.2 emission inventories for NO2 emissions in 1995 (For the Russian Federation, EMEP figures apply for the European part of territory only).

OECD EUROPE				
Area	**NOx, EMEP (Gg)**	**NOx, EDGAR (Gg)**	**Difference (Gg)**	**Difference (%)**
Austria	182.7	202.0	-19.3	-11
Belgium	324.9	371.4	-46.5	-14
Denmark	261.4	223.0	38.4	15
Finland	258.0	207.6	50.4	20
France	1709.0	1482.7	226.3	13
Germany	1967.0	2001.2	-34.2	-2
Greece	309.0	327.8	-18.8	-6
Iceland	28.4	8.5	19.9	70
Ireland	115.3	122.3	-7.0	-6
Italy	1768.0	1533.1	234.9	13
Luxembourg	21.0	34.0	-13.0	-62
Netherlands	483.5	450.3	33.2	7
Norway	222.7	157.9	64.8	29
Portugal	357.8	282.0	75.8	21
Spain	1355.0	1204.2	150.8	11
Sweden	309.2	234.0	75.2	24
Switzerland	120.0	124.5	-4.5	-4
United Kingdom	2088.0	2220.1	-132.1	-6
Sum	**11880.9**	**11186.6**	**694.3**	**6**

Table 8 (Cont'd) Comparison between EMEP and EDGAR 3.2 emission inventories.

EASTERN EUROPE				
Albania	24.0	13.5	10.5	44
Bosnia and Herzegovina	80.0	25.5	54.5	68
Bulgaria	266.0	195.0	71.0	27
Croatia	65.7	76.0	-10.3	-16
Czech Republic	412.0	270.7	141.3	34
Hungary	190.1	222.1	-32.0	-17
Poland	1120.0	1135.3	-15.3	-1
Romania	319.0	371.5	-52.5	-16
Slovakia	174.0	155.7	18.3	11
Slovenia	67.0	62.3	4.7	7
The FYR of Macedonia	30.4	33.6	-3.2	-11
Yugoslavia	59.0	161.3	-102.3	-173
Sum	**2807.2**	**2722.6**	**84.6**	**3**
FORMER USSR				
Armenia	14.9	18.2	-3.3	-22
Belarus	195.0	252.5	-57.5	-29
Estonia	42.1	60.6	-18.5	-44
Georgia	26.6	13.0	13.6	51
Kazakhstan	76.0	652.7	-576.7	-759
Latvia	41.8	49.6	-7.9	-19
Lithuania	65.0	81.5	-16.5	-25
Republic of Moldova	38.2	55.2	-17.0	-44
Russian Federation	2570.0	5148.1	-2578.1	-100
Ukraine	531.0	2411.9	-1880.9	-354
Sum	**3600.5**	**8743.3**	**-5142.7**	**-143**

While the EDGAR emission data rely on international activity data and emission factors from the literature, the EMEP emission data are based on the individual countries' best estimates and or measurements of activity data and emission factors. The methodology used to estimate emissions should be comparable between countries, through the use of the EMEP/CORINAIR emission inventory Guidebook. There is however currently a lack of complete transparency in the EMEP reporting of emissions, and it is difficult to validate the inventories. The new Guidelines for reporting and estimating emissions data to UNECE/EMEP (UNECE, 2002), is aiming at enhancing the completeness, transparency, consistency, comparability and accuracy of the reported data.

5.3. The United States Environmental Protection Agency (USEPA) National Inventories

The Emission Factor and Inventory Group of the United States Environmental Protection Agency (USEPA) in Research Triangle Park, NC, USA has prepared over the past years a national database of air emissions information with input from numerous US State and local air agencies, from Native American tribes, and from industry. This database contains information on stationary and mobile sources that emit so-called criteria air pollutants (Criteria air pollutants are those for which EPA has set health-based standards. Currently the following species are included as criteria pollutants: sulfur dioxide (SO_2), ozone (O_3), nitrogen oxides (NO_x), carbon monoxide (CO), lead (Pb), and particulate matter (PM)) and their precursors, as well as hazardous air pollutants (HAPs). The database includes estimates of emissions, by source, of air pollutants in each area of the country on an annual basis. The National Emission Inventory (NEI) includes emission estimates for all 50 States, the District of Columbia, Puerto Rico, and the Virgin Islands. Information and data are available at the NEI website: http://www.epa.gov/ttn/chief/trends/. Emission estimates for individual point or major sources (facilities), as well as county level estimates for area, mobile and other sources, are currently available for years 1985 through 1999 for criteria pollutants, and for years 1996 and 1999 for HAPs (see Figure 6 for resulting SO_2 emissions in 1998).

Data from the NEI are used for air dispersion modelling, regional strategy development, regulation development, air toxics risk assessment, and following trends in emissions over time. For emission inventories prior to 1999, criteria pollutant emission estimates were maintained in the National Emission Trends (NET) database and HAP emission estimates were maintained in the National Toxics Inventory (NTI) database. Beginning with 1999, criteria and HAP emissions data are being prepared in a more integrated fashion in the NEI, which combines the NET and the NTI.

Four of the six criteria pollutants are included in the NEI database: CO, NO_x, SO_2, and PM (PM_{10} and $PM_{2.5}$). The NEI includes emissions of Volatile Organic Compounds (VOC) emitted from motor vehicle fuel distribution, chemical manufacturing, and other solvent uses because VOC, along with NO_x, are ozone precursors. Emissions of NH_3 are also included in

the NEI because this species is a precursor of PM.

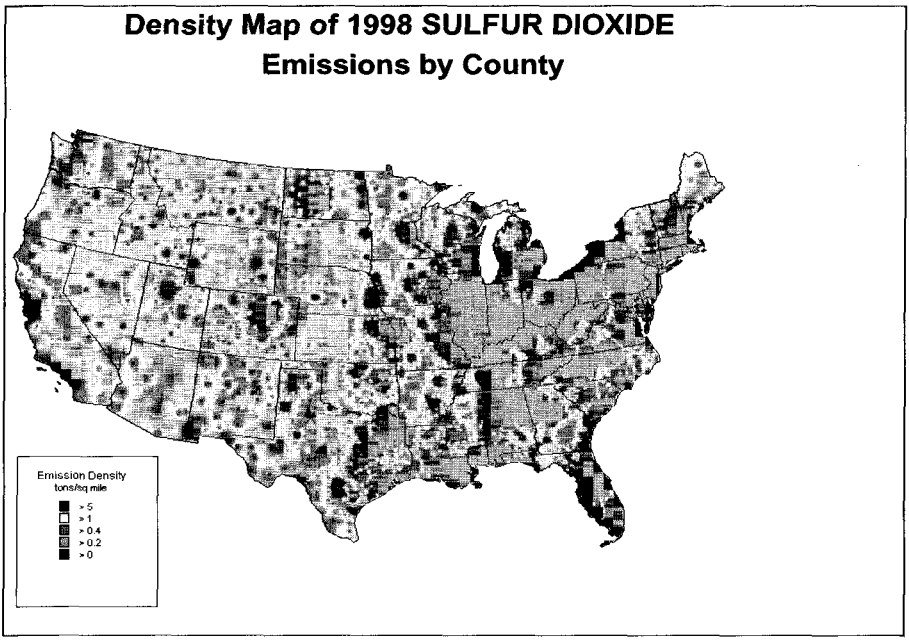


Figure 6 (see plate 6). Emissions of SO_2 in the United Stated in 1998 (short tons/mile^2). From EPA web site http://www.epa.gov/ttn/chief/trends.

The NEI database defines three classes of criteria air pollutant sources:

i) Point sources - stationary sources of emissions, such as an electric power plant, that can be identified by name and location. A "major" source emits a threshold amount (or more) of at least one criteria pollutant, and must be inventoried and reported. Many states also inventory and report stationary sources that emit amounts below the thresholds for each pollutant.

ii) Area sources - small point sources such as a home or office building, or a diffuse stationary source, such as wildfires or agricultural tilling. These sources do not individually produce sufficient emissions to qualify as point sources. Dry cleaners are one example, i.e., a single dry cleaner within an inventory area typically will not qualify as a point source, but collectively the emissions from all of the dry cleaning facilities in the inventory area may

be significant and therefore must be included in the inventory. The NEI includes facility data for some area sources and aggregated emission estimates at the county level for the remaining area sources.

iii) Mobile sources - any kind of vehicle or other mobile equipment with a gasoline or diesel engine: on-road vehicles, non-road 2- and 4-stroke and diesel engines, off-road vehicles, aircraft, locomotives, and commercial marine vessels. The NEI includes aggregated emission estimates at the county level for mobile sources.

The main sources of criteria pollutant emissions data for the NEI are:

- Stationary sources:
  - For electric generating units - EPA's Emission Tracking System / Continuous Emissions Monitoring Data, Department of Energy fuel use data, and EPA's Clean Air Market program.
  - For other large stationary sources - state and local environmental agencies, with data from older inventories included where no state data were submitted.

- Mobile sources:
  - For on-road mobile sources (cars, trucks, etc.) - the Federal Highway Administration's estimate of vehicle miles travelled and emission factors from EPA's MOBILE Model (US Environmental Protection Agency, 2002).
  - For non-road mobile sources (locomotives, construction equipment, etc.) - EPA's NONROAD Model (Pechan et al., 2002 and http://www.epa.gov/ttn/chief/net/index.html#1999)

- For stationary area sources - state data, EPA-developed estimates for some sources, and older inventories where no state or EPA data were submitted.

Hazardous air pollutants, also known as toxic air pollutants, are those pollutants that are known or suspected to cause serious health problems. They are defined in the US Clean Air Act (CAA) which identifies a list of 188 pollutants as HAPs. The list of HAPs includes relatively common pollutants such as benzene, formaldehyde, methanol, and asbestos, as well as

numerous less common substances.

The NEI database includes emission estimates for the 188 HAPs from major stationary, area sources, and mobile sources, as defined in the CAA. As for the criteria pollutants, the HAP emission sources are grouped in three classes:

1. the major sources, which correspond to stationary (point) sources that emit or have the potential to emit 10 tons per year or more of any listed HAP or 25 tons per year or more of a combination of listed HAPs. The NEI includes data for each individual major source, including the name and location of the facility.

2. area and other stationary sources that emit or have the potential to emit less than 10 tons per year of a single HAP and less than 25 tons per year of all HAPs combined, for example, neighbourhood dry cleaners and gas stations. Although emissions from individual area sources are often relatively small, collectively their emissions can be of concern. Other stationary sources of emissions, such as wildfires and prescribed burning, are addressed through the burning policy agreed to by EPA and the Department of Agriculture. The NEI includes aggregated emission estimates at the county level for these other sources.

3. mobile sources, with the same definition as for criteria pollutants. The NEI includes aggregated emission estimates at the county level for these sources.

The estimates of these HAP emissions rely on various sources: State, local, and tribal HAP inventories, existing databases related to EPA's Maximum Achievable Control Technology (MACT) programs to reduce HAP emissions, Toxic Release Inventory (TRI) data, the mobile source methodology developed by EPA's Office of Transportation and Air Quality (OTAQ), and the use of emission factors and activity data for stationary non-point sources. More information about the NEI database and the compilation of criteria pollutant and HAP emissions inventories, and links to the database, are available on EPA's website for the Clearinghouse for Inventories and Emission Factors at www.epa.gov/ttn/chief.

5.4. Asian Inventories

Inventories of base-year 1995 or later covering East, Southeast, and/or South Asia are summarized in Table 9. Emission inventories for China, Japan and India are also included.

Table 9: Summary of research for regional emission inventory in Asia. BC refers to black carbon and OC to organic carbon.

Research group	Base year	Domain	Species	Grid size, degree	References
ACESS	2000	All Asia	SO_2, NO_x, CO, NMVOC, BC, OC, NH_3, CH_4	1	ACESS (2002)
FRSGC	1995	All Asia	SO_2, NO_x, CO, NMVOC, BC, NH_3, N_2O, CH_4	0,5	Ohara et al. (2001), Yan et al. (2002)
RAINS-ASIA	1995	All Asia	SO_2	1	IIASA (2001)
Streets et al.	1985-1997	All Asia	SO_2, NO_x	-	Streets et al. (2001, 2002)
Klimont et al.	1995	East Asia	SO_2, NO_x, NMVOC, NH_3	1	Klimont et al. (2001)
Murano et al.	1994-1996	East Asia	SO_2, NO_x, NMVOC, NH_3	0,5	Murano et al. (2002)

5.4.1 Emissions

5.4.1.1 The ACCESS inventory

Streets and co-workers at Argonne National Laboratory (ANL) prepared emission inventories for use during the ACE-Asia and TRACE-P field campaigns carried out in East Asia/Western Pacific region in spring 2002, and made the data available on the web (Ace-Asia and TPACE-P Modelling and Emission Support System: ACESS, 2002). The campaigns focused on the characterization of gaseous and aerosol species in Asian outflow to the western Pacific Ocean and the inventories includes SO_2, NO_x, CO, NMVOC, BC (black carbon), OC (organic carbon), NH_3, and CH_4. Twenty-two countries and regions in East, Southeast and South Asia are included, and 1° x 1° grid maps for the base year 2000 were provided. NMVOC from

biomass burning and other biogenic sources, Mg and Ca from soils, CH_4 from wetlands, and SO_2 from volcanoes were also included in the ACESS inventories.

5.4.1.2 The RAINS-Asia inventory

The Regional Air Pollution Information and Simulation (RAINS-Asia) is a project organized by the International Institute for Applied Systems Analysis (IIASA) and funded by the World Bank for the purpose of constructing a policy tool for the mitigation of acid rain in Asia. In this study emission inventories for SO_2 with base years of 1990 and 1995, and also projections from 2000 to 2030 are estimated, and the results are available in a CD-ROM (IIASA, 2001). Based on these inventories Streets et al. (2000, 2001) reported trends of country-bases emission of SO_2 and NO_x in Asia during 1985 and 1997.

5.4.1.3 The FRSGC inventory

Frontier Research System for Global Change (FRSGC) is now constructing emission inventories for the purpose of studying air quality change/climate change in Asia (Ohara et al., 2001). The inventories include country-based data for SO_2, NO_x, CO, NMVOC, and BC for 1995. Updates for 2000, as well as inventories of NO_x, NH_3, N_2O, and CH_4 from agricultural sources with consideration of regional specificity in Asia are underway (Yan et al, 2003;, Yamaji et al., 2003). Gridded data at a 0.5° x 0.5° resolution will be available on the web in the near future.

5.4.2 Comparison between Asian emission inventories

5.4.2.1 Sulphur Dioxide (SO_2)

A summary of the SO_2 emissions in Asia from different inventories is presented in Table 10. Emissions from country-based inventories typically agree within 15%, and total emissions in Asia agree within 4% except for the EDGAR 3.2 values.

Table 10: Summary of Asian SO_2 emissions (Tg SO_2/year)

Inventory / Area	ACESS* (2000)	FRSGC (1995)	RAINS (1995)	Streets et al. (1995)	Klimont et al. (1995)	Murano et al. (1995,96)	EDGAR 3.2 (1995)
East Asia Total	22.6	28.3	26.5	28.6	24.6	26.3	42.3
Southeast Asia Total	3.1	3.0	3.3	3.1	-	-	3.8
Indian Subcontinent Total	7.1	5.9	6.2	6.7	-	-	7.4
Ships	1.1	-	0.8	-	-	-	*)
Asia Total	**33.9**	**37.2**	**36.8**	**38.5**	**-**	**-**	**53.5**

*) Global grid-based emissions include main shipping routes in Asia.

Table 11 compares results for China from Xue et al. (1998) and Streets et al. (2000) with the values estimated by the State Environmental Protection Administration, China (SEPA). A recent decreasing trend in SO_2 emission is discernible in SEPA's data, possibly caused by an effort to change to low sulphur coal and to convert from coal to other fuels.

Table 11: Summary of emissions in China (Tg/year)

Inventory	SEPA			Xue et al.	Streets et al.		
Component	(1995)	(1997)	(1998)	(1995)	(1995)	(1996)	(1997)
SO_2	23.7	22.7	20.9	23.7	25.9	26.4	25.1
NO_x	-	-	-	10.7	11.2	-	12.5

EDGAR 3.2 emissions from China are estimated at 35 Tg/yr, compared to 20-25 Tg/yr from inventories by SEPA, Xue and Streets and coworkers. In EDGAR all other East Asian emissions are overestimated by more than a factor of 2-3, except emissions from Mongolia which are greatly underestimated. The region-wide estimates presented in Table 9 reflect what are considered to be the best information on sulphur content of fuels and the

results of control policies in this area. Because the EDGAR datasets are the most widely used inventories for global modelling, the significant discrepancy in East Asia should be resolved.

Table 12: Summary of emissions in India (Tg/year)

Inventory / Compound	Garg et al. (1995)	Reddy & Venkataraman [1] (1996-97)	ACESS [1] (2000)	FRSGC (1995)
SO_2	4.64	4.33	5.46	4.93
NO_x	3.46	-	4.05	4.58
BC	-	0.31	0.52	0.51
OC	-	0.69 [2]	2.19	-

1) Excluding forest biomass for comparison with other results.
2) Organic Matter/OC ratio assumed as 1.3 according to Reddy and Venkatraman (2002a,b).

Table 12 compares estimates for India in regional inventories with those obtained by Indian researchers; these estimates agree within 20%. For South East Asia and South Asia agreement between EDGAR 3.2 and other studies falls within a range of 20% although EDGAR 3.2 is in the upper end of estimate.

5.4.2.2 Nitrogen Oxides (NO_x)

Estimates of NO_x emissions are shown in Table 13. Estimates are within 25% for most of the major emitting countries and for the Asian total, including EDGAR. The EDGAR 3.2 estimate is at the upper end but still within the scatter of the estimates. The estimates of Xu et al. for China agree very well with other studies. The value for India by Garg et al. (2001) is at the lower end in the 25% range.

Table 13: Summary for NO_x emissions (Tg NO_2/year)

Researcher (base year) / Area	ACESS *) (2000)	FRSGC (1995)	Streets et al. (1995)	Klimont et al. (1995)	Murano et al. (1995,96)	EDGAR 3.2 (1995)
East Asia Total	14.9	14.8	17.2	13.9	14.4	17.8
Southeast Asia Total	3.1	2.9	3.2	-	-	4.1
Indian Subcontinent Total	4.8	5.4	5.2	-	-	6.5
Asia Total	**22.7**	**23.1**	**25.6**	**-**	**-**	**28.4**

5.4.2.3 Carbon Monoxide (CO)

For CO (Table 14) substantial differences can be seen in Southeast Asia, especially between ACESS, FRSGC and EDGAR inventories. Modelling results and observational data in ACE-Asia indicate that CO emissions in China are underestimated. This underestimate is believed to be mainly in the emissions from the domestic sector where biofuels and coal are widely used. Further studies would be necessary to reduce the uncertainties in the emission factors of CO from biogenic fuels and coal, because these factors are also very important in the emissions estimates from other developing countries in Asia.

Table 14: Summary for CO emissions (Tg CO/year)

Researcher (base year) / Area	ACESS *) (2000)	FRSGC (1995)	EDGAR 3.2 (1995)
East Asia Total	115.0	92.1	111.5
Southeast Asia Total	34.0	23.3	70.6
Indian Subcontinent Total	62.2	50.7	75.0
Asia Total	**211.4**	**166.1**	**257.1**

*) Excluding forest biomass burning for comparison with other results.

5.4.2.4 Other species

The agreement for NMVOC and NH_3 is remarkably good as seen in Tables 15 and 16. However, this does not mean that the accuracy of the inventories is high but rather that the values of emission factors and activity data are limited and the same values are used in most inventories. Estimates of NMVOC emissions for 1995 in the FRSGC inventory were provided by collaboration with Streets and are essentially the same as the estimates in the ACESS inventory for 2000. Table 12 includes the estimates for BC and OC It is not surprising that the discrepancies in the emissions for these species are large, and more elaboration by both top-down observation approach and bottom-up emission factor experiments are necessary.

Table 15: Summary for NMVOC emissions (Tg/year)

Inventory / Country	ACESS * (2000)	FRSGC (1995)	Klimont et al. (1995)	Murano et al. (1994-96)	EDGAR 3.2 (1995)
East Asia Total	18.5	18.5	17.1	17.9	19.5
Southeast Asia Total	11.1	11.1	-	-	10.8
Indian Subcontinent Total	10.7	10.7	-	-	10.9
Asia Total	**40.2**	**40.3**	-	-	**41.1**

Table 16: Summary for NH_3 emissions (Tg NH_3/year)

Inventory / Area	ACESS * (2000)	IIASA (1995)	Murano et al. (1995,96)	Bouwman et al. (1997) (1990)
East Asia Total	14.2	12.7	13.1	10.6

*) Excluding forest biomass burning for comparison with other results.

In conclusion, although SO_2 and NO_x inventories should be rather mature, large discrepancies exist between EDGAR 3.2 and other region-wide inventories, especially for China and other East Asian countries. For CO,

NMVOC, NH_3, BC, and OC verification of emission inventory data using observational data with regional representativeness is absolutely necessary.

6. PAST HISTORY OF ANTHROPOGENIC EMISSIONS

6.1 Introduction

Despite the importance of knowing the extent of past anthropogenic emissions, only a few attempts have been made to estimate time series of global historical emissions (especially before 1970), even less on a relatively detailed sectoral basis and on a high resolution grid-basis. For isolated species several inventories are available. For greenhouse gas emissions, Andres et al. (1999) estimated CO_2 emissions from fossil fuel combustion and cement production by country and 1° x 1° grid for the period 1751 to the present. Stern and Kaufmann (1995) estimated global emissions of CH_4 for the years 1860-1993. For acidifying gases several studies have estimated SO_2 emissions. Hameed and Digon (1988) estimated emissions in the period 1960-1980 for the USA, OECD Europe and the rest of the World on a 10° x 10° grid. Mylona (1996) estimated emissions for individual European countries, including Eastern European countries and SU for the period 1880-1990 on a 150x150 km grid. Lefohn et al (1999) estimated detailed emissions from 1850 to 1990 with data per country and for some sectors.

Global gridded emissions of CO_2, CO, CH_4, NMVOC, SO_2, NO_x, N_2O, and NH_3 by sector for the period 1890-1990 have been estimated by Van Aardenne et al. (2001) using a consistent and transparent methodology. The emissions have been computed using an emission factor approach. The historical activity data were taken from the HYDE database (Klein Goldewijk and Battjes, 1997) supplemented with other data and estimates developed during this work. Historical emission factors per process were based on uncontrolled emission sources included in EDGAR V2.0 (Olivier et al., 1996; 1999a). The emission database describes anthropogenic source categories such as fossil fuel production and combustion, industrial production, agricultural practices, waste handling, and land-use related activities. Although a consistent database of historical emissions is a useful tool for modeling past atmospheric changes due to human activities, users should be aware of the limitations of such a large-scale historical emission

inventory. Information on activities and emission factors in the past is limited, uncertain. and sometimes non-existent, his leads in some cases to scaling back of current activity data rates using indicators and the application of global aggregated emission factors. The methodology used for estimating emissions from fossil fuel combustion will be described as an example.

6.2 Methodology for fossil fuel combustion emissions

Because emissions from fuel combustion differ between sectors, fuel types, and regions the combustion of coal, oil or gas for the power generation, industry, transport and residential energy sectors were addressed separately. For the entire period there were no resources which provided information at the required detail. Detailed energy statistics by country and for several fuel type and sectors were available from the International Energy Agency (IEA, 1994) only for the period 1970-1990. An activity data set was derived. for two other periods, 1930-1960 and 1890-1920. For the years 1930, 1940, 1950 and 1960 energy consumption information was derived based on Darmstadter (1971). The Darmstadter study provided total annual consumption statistics for three main fuel types (solids, liquids and gas) together with information on electricity and hydroelectricity consumption. The data were available for selected years only by region and for some countries without breakdown by sector. To differentiate between the four emitting sectors the following methodology was used. The amount of fossil fuel needed for power generation was determined by combining data on hydroelectricity production (Darmstadter, 1971), data on efficiency in electricity production in the past (Etemad et al., 1991) and the data on fuel mix used to produce electricity from Darmstader (1971). The amount of fuel used for non-power generation was determined by subtracting the amount and type of fuel used for power generation from the total fuel consumption of each type. To distinguish between industrial, transport and residential energy use an additional step was needed. Based on detailed IEA statistics (IEA, 1994) the ratio between industry, transport and residential energy use could be determined for the situation in the 1970's. To estimate the ratio of energy use in the industry, transport and residential sector for years prior to 1970, the sectoral split for 1970 was scaled back in time using indicators that can be associated with fuel use in the different sectors. The consumption of fuel type per sector for the years 1930, 1940, 1950 and 1960 were estimated

by dividing the detailed IEA data by the 1970 indicator followed by multiplying this value with the indicator value for the other years. For industry the indicator was value-added industry (contribution of the industrial sector to Gross Domestic Product, GDP, World Bank, 1993; Madisson, 1994).

Table 17: Emission factors in rounded figures as used for calculation of fossil fuel combustion emissions in the period 1890-1970 (defined on element basis, e.g. C and N). For the period 1970-1990 country-specific emission factors were used (Olivier et al., 1999b). For a description of data sources see Van Aardenne et al. (2001).

	CO_2 kg C/GJ	CO g C/GJ	CH_4 g C/GJ	NMVOC g C/GJ	SO_2 g S/GJ	N_2O g N/GJ	NO_x g N/GJ	NH_3 gN/GJ
Power plants								
Coal	26	9	1	2	450	0.6	122	0
Oil	19	9	2	3	600	0.4	67	0
Gas	15	9	1	5	10	0.1	46	0
Domestic								
Coal	26	2100	225	200	Region	0.9	25	0
Oil	19	13	8	3	al[a]	0.4	15	0
Gas	15	27	...	10	200	0.1	15	0
					5			
Industry								
Coal	26	60	8	20	550	0.9	82	2.5
Oil	19	9	2	2	400	0.4	18	0
Gas	15	13	4	5	10	0.1	34	0
Transport								
Coal	26	64	8	20	450	0.9	82	-
Oil	19	4300	15	1300	100	0.4	183	0.1
Gas	15	...	...	10	10	0.1	...	-

[a] Domestic coal (kg S GJ^{-1}): Canada, 550; United States, 350; Latin America, 500; Africa, 300; OECD Europe, 450; eastern Europe, 450; former SU, 400; Middle East, 700; India region, 300; China region, 500; east Asia, 350; Oceania, 400; and Japan, 250.

The number of vehicles derived from the HYDE database was used to scale the energy use in the transportation sector. For the residential sector GDP per capita was used as indicator (World Bank, 1993; Madisson, 1994). For the years 1890-1920 the energy consumption per fuel (coal, oil, gas) per

sector (power generation, industry, transport and residential) and per region were scaled back in time by using coal, oil and gas production data (Darmstadter, 1971; Etemad et al., 1991).

Emissions in the period 1970-1990 were calculated using country specific emissions factors (Olivier et al., 1999a). Because data were unavailable it was assumed that the 1990 EDGAR V2.0 (Olivier et al., 1999a) emission factors reflect the factors without emission controls before 1970. Pre-1970 emissions were calculated per sector and fuel type using these emission factors for regions known to have no emission controls. Because SO_2 emissions from coal depend on fuel sulphur content (for which regional data were available) regional emission factors for SO_2 from coal were used, which also represented uncontrolled emissions. Table 17 presents the emission factors used for 1890-1970.

6.3 Results and uncertainties

By using activity data and emission factors as described in Van Aardenne et al (2001) and presented for fossil combustion in Section 6.2, emissions of CO_2, CO, CH_4, NMVOC, SO_2, NO_x, N_2O, and NH_3 were calculated for the period 1890-1990 and interpolated to a 1° x 1° longitude/latitude grid. Global emissions for the eight species by source category are presented in Figure 7. As shown in the figure for several species (e.g. CO_2, SO_2) the energy sector is the most important source of emissions over the years. For other species (e.g. CH_4, N_2O and NH_3), agricultural practices are most important. For some species a shift in important emission sources is visible. For example, NO_x emissions in 1890 were mainly from agricultural lands while after the 1920's energy related emissions became important. Although these data are based on the EDGAR 2.0 methodology (Olivier 1999a), some difference between the two datasets exist. For example, the use of aggregated emission factors will lead to differences where EDGAR v2.0 applied detailed emission factors.

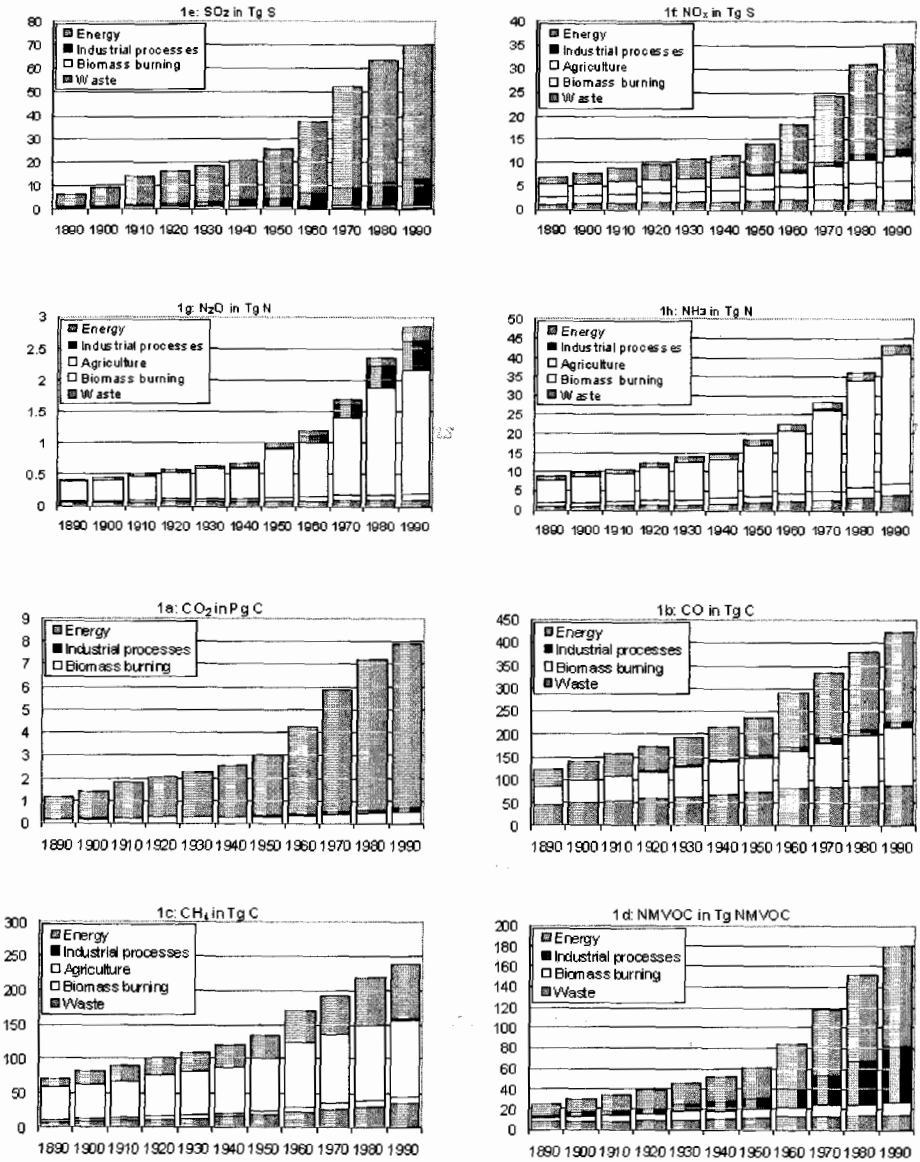


Figure 7. Estimated anthropogenic emissions in the period 1890-1990.

By comparing different emission estimates possible inaccuracies in the inventories could become apparent. For example, Figure 8 presents an overview of CO_2 emissions from fossil fuel combustion and cement production computed by Van Aardenne et al. (2001), Keeling (1994), and Marland et al. (1994). For the period 1890-1960 the global emissions are in good agreement (<5% difference). For the post-1960 years the Marland et al. estimates are somewhat higher than the Van Aardenne et al. estimates.

Possible reasons for these discrepancies are that international air transport emissions (which account for 2% of the emissions in 1990) are not included in the Van Aardenne et al. dataset and that activity data from different sources were used: Marland et al. used UN data, Van Aardenne et al used IEA data.

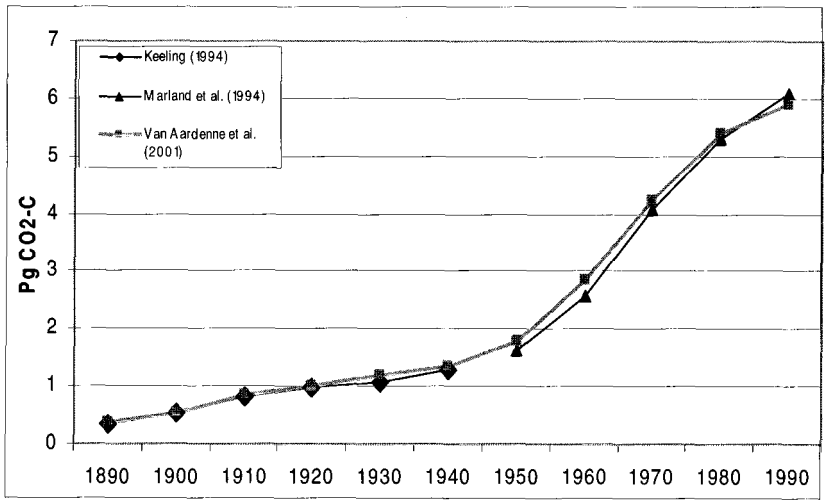


Figure 8. Comparison of fossil fuel and industrial CO_2 emissions from Keeling (1994), Marland et al. (1994) and Van Aardenne et al. (2001).

In Figure 9 global NO_x emissions for the years 1960, 1970 and 1980 are compared between Hameed and Dignon (1988) and Van Aardenne et al. (2001). The estimates of Van Aardenne et al. seem to be significant lower, which might be related to differences in the methodology. Regional estimates for the USA are compared with Gschwandtner et al. (1985). Regional emissions for the USA are in rather close agreement between the two estimates.

The results of historical emission calculations are associated with significant uncertainties. This is illustrated in Figure 9. Even for present-day emissions, estimates based on relatively more reliable activity data and emission factors, are uncertain (see section 5). Historical activity data are mostly based on studies using national or international statistics agencies. Although the quality of these data is difficult to assess, this information is probably the best available with consistent source definitions across countries. Where no activity data are available, assumptions have to be made on processes leading to the emission activity. This is of course, an important source of inaccuracy. The use of constant aggregated emission factors for the period 1890-1970 instead of representative emissions factors for processes in the past is another major source of inaccuracy. However, since prior to 1970 both verified emission factors or activity data such as IEA data are not available, assumptions on historical activities and emission factors have to be made or historical emission inventories cannot be compiled. In order to understand past atmospheric changes these types of emission inventories are necessary; however users should be aware of their large inaccuracies.

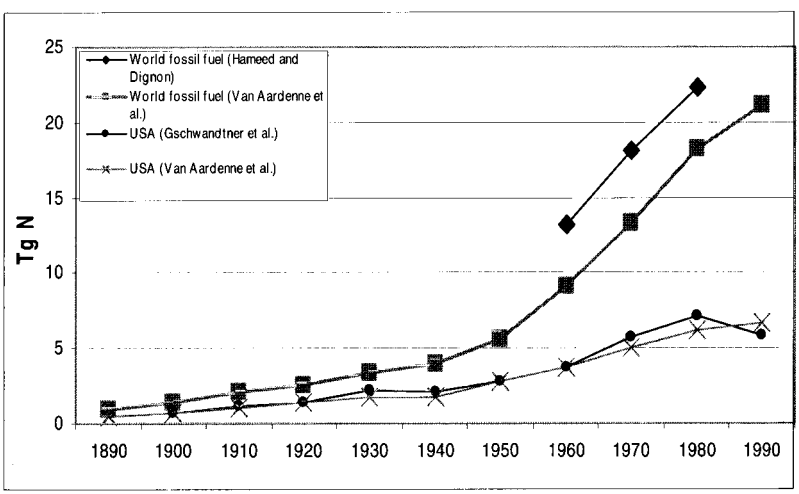


Figure 9. Comparison of global NO_x emissions (Hameed and Dignon (1988) vs. Van Aardenne et al. (2001)) and United States of America emissions (Gschwandtner et al. (1985) vs. Van Aardenne et al. (2001)).

7. FUTURE WORK

The importance of having accurate estimates of emissions to the atmosphere of trace species is becoming more and more critical in the development of our basic scientific knowledge and to better control these emissions in the mitigation of detrimental effects such as adverse effects on human health, acid rain, and climate change. As we so graphically saw in the Marland et al. (1999) article the resulting emissions estimates may be very close when comparing percentages, but can result in large absolute differences, and there is currently no way of identifying which results are more accurate. Therefore, 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.

The inventories described in this chapter are widely used for atmospheric chemistry studies (e.g. GEIA/IGAC) and within the environmental policy making (e.g. EMEP/IPCC). Although national projects such as EDGAR have been sponsored over the years, increased and concerted efforts in emission inventory development are necessary to improve the quality of the emission estimates and thus the understanding of the changing composition of the atmosphere and its effects on humans and nature. Moreover, high quality inventories are a prerequisite for developing cost-effective environmental policies and realistic projections of future emissions. GEIA has attempted to bring together on a voluntary basis investigators developing emissions estimates in an attempt to make the whole better than its parts. In this it has been partially successful; however, much more is needed, both in terms of acquiring additional resources for inventory compilation and in the revitalization of the cooperative efforts initiated by GEIA. Important aspects of these efforts include capacity building in developing countries to improve their emission estimates and the need for feedback from the user community on the quality of the inventories. For this a close co-operation between the atmospheric-chemistry community, the policy community, and the emission inventory community is essential.

8. SUMMARY

The mathematical modelling of the transport and transformation of trace species in the atmosphere is one of the scientific tools currently used to assess atmospheric chemistry, air quality, and climatic conditions. From the scientific but also from the management perspectives accurate inventories of emissions of the trace species at the appropriate spatial, temporal, and species resolution are required. The chapter has discussed bottom-up methodologies to estimate global and regional emissions. These methodologies are based on activity data, emission factors (amount of emissions per unit activity), and for some inventories additional parameters (such as sulphur content of fuels). To compile regional and global inventories researchers can either bring together estimates made at the national or sub-national level by national experts or directly estimate emissions based on activity rates from reports compiled by multi-national organizations such as the United Nations and the International Energy agency and on emission factors and other information available in the literature. In all cases the data used must be checked for transparency, consistency, comparability, completeness and accuracy. These emissions estimates must now be given finer spatial (usually gridded), temporal, and for some inventories species resolution. The location of major stationary sources (power plants, industrial complexes) is usually known, so the emissions can be directly assigned to the appropriate grid cell. For emissions from other activities, such as transportation, spatial resolution is obtained via the use of surrogate information, such as population distribution, land use, traffic counts, etc. which already exists in or can directly be converted to gridded form. To obtain finer temporal resolution (seasonal, daily, weekday/weekend, etc.) auxiliary information such as plant schedules, traffic counts, etc. is required. Speciation factors have been and are being developed to speciate inventories of hydrocarbons (individual species or groups of species), NO_x (NO, NO_2) and particulate matter ($PM_{2.5}$, PM_{10}; by species).

9. REFERENCES

ACESS, emission database available from http://www.cgrer.uiowa.edu/ACESS /acess_index.htm, 2002.

Andres, R. J., D. J. Fielding, G. Marland, T. A. Boden, N. Kumar, and A. T. Kearney, Carbon dioxide emissions from fossil fuel use, 1751–1950. Tellus, Serie B, 51, 759– 765, 1999.

Arndt, R.L., G.R. Carmichael, D.G. Streets, and N. Bhatti, Sulphur Dioxide Emissions and Sectoral Contributions to Sulphur Deposition in Asia, Atmos. Env., 31, 1553-1572, 1997.

Baldasano, J.M., and H. Power, Air Pollution Emissions Inventories, in Advances Series in Air Pollution. Chapter 1: Guidelines and Formulation of an Upgrade Source Emissions Model for Atmospheric Pollutants, pp. 238, Computational Mechanics Publications, Southampton, UK, 1998.

Benkovitz, C.M., M.T. Scholtz, J. Pacyna, L. Tarrasón, J. Dignon, E.V. Voldner, P.A. Spiro, J.A. Logan, and T.E. Graedel, Global Gridded Inventories of Anthropogenic Emissions of Sulfur and Nitrogen, J. Geophys. Res., 101, 29239-29253, 1996.

Benkovitz, C.M., and T.E. Graedel, The IGAC Activity for the Development of Global Emissions Inventories: Description and Initial Results., in *85th Annual Meeting of the Air and Waste Management Association, June 21-26, 1992*, pp. 2-10, Air & Waste Management Association, Pittsburgh, PA, Kansas City, MO, 1992.

Bouscaren, R., CORINAIR 1990, in First Meeting of the Task Force on Emissions Inventories, edited by J.M.P.a.H.D. G. McInnes, Norwegian Institute for Air Research, London, England, 1992.

Bouwman, A.F.,, K.W. van der Hoek, and J.G.J. Olivier. Uncertainties in the global source distribution of nitrous oxide. J. Geophys. Res., 100, 2785-2800, 1995.

Bouwman, A.F., D.S. Lee, W.A.H. Asman, F.J. Dentener, K.W. Van Der Hoek and J.G.J. Olivier. A Global High-Resolution Emission Inventory for Ammonia, Global Biogeochemical Cycles, 11, 561-587, 1997.

British Petroleum, BP Statistical Review of World Energy 2002, BP Distribution Services, Bournemouth, Dorset (UK), 2002.

Byun, D.W., and J.K.S. Ching, Science Algorithms of the EPA Models-3 Community Multiscale Air Quality (CMAQ) Modeling System, Office of Research and Development U.S Environmental Protection Agency, Research Triangle Park, NC, 1999.

Corbett, J.J. and P.S. Fischbeck, Emissions From Ships. Science, 278, 823-824, 1997.

Corbett, J.J., P.S. Fischbeck, and S.N. Pandis, Global Nitrogen and Sulfur Emissions Inventories for Oceangoing Ships, J. Geophys. Res., 104, 3457-3470, 1999.

Darmstadter, J., Energy in the World Economy. Balimore: John Hopkins Press, 876 pp, 1971.

Doorn, M.R.J., R.P. Strait, W.R. Barnard, and B. Eklund. Estimates of global greenhouse gas emissions from industrial and domestic waste water treatment. Report no. NRMRL-RTP-086. R 8/18/97. Pechan & Ass., Durham, 1997.

Doorn, M.J. and D.S. Liles. Quantification of methane emissions and discussion of nitrous oxide, and ammonia emissions from septic tanks, latrines, and stagnant open sewers in the world. EPA, Washington DC, USA. EPA report EPA-600/R-99-089, October 1999.

EMEP/CORINAIR, 2001 Atmospheric Emission Inventory Guidebook, Third Edition, 2001'. (http://reports.eea.eu.int/technical_report_2001_3/en)

Etemad, B., P. Bairoch, J. Luciani, and J.-C. Toutain, World Energy Production 1800–1985, Geneve: Libraire Droz, 272 pp., 1991.

Foell, W., M. Amann, G. Carmichael, M. Chadwick, J.P. Hettelingh, L. Hordijk, and Z. Dianwu, RAINS-ASIA: AN ASSESSMENT MODEL FOR AIR POLLUTION IN ASIA, The World Bank, Washington, DC, 1995.

Food and Agriculture Organization of the United Nations, FAOSTAT, Food and Agriculture Organization of the United Nations, 2000.

Friedrich, R., B. Wickert, U. Schwarz, and S. Reis, Improvement and Application of Methodology and Models to Calculate Multiscale High Resolution Emission Data for Germany and Europe. In: GENEMIS Annual Report 1999, pp. 119, Iernational Scientific Secretariat, GSF-Forschungszentrum für Umwelt und Gesundheit GmbH, Munich, Germany, 2000.

Friedrich, R., B. Wickert, P. Blank, S. Emeis, W. Engewald, D. Hassel, H. Hoffmann, H. Michael, A. Obermeier, K. Schäfer, T. Schmitz, A. Sedlmaier, M. Stockhause, J. Theloke, and F.-J. Weber, Development of Emission Models and Improvement of Emission Data for Germany, *J. Atmos. Chem.*, *42*, 179-206, 2002.

Friedrich R and Reis S. (eds), Emissions of Air Pollutants - Measurements, Calculation, Uncertainties - Results from the EUROTRAC Subproject GENEMIS. Springer Publishers, in preparation, 2003.

Galbally, I., The International Global Atmospheric Chemistry Programme, Commission on Atmospheric Chemistry and Global Pollution of the International Association of Meteorology and Atmospheric Physics, 1989.

Garg, A., P.R. Shukla, S. Bhattacharya, and V.K. Dadhwal, Sub-region (district) and sector level SO_2 and NO_x emissions for India: assessment of inventories and mitigation flexibility, Atmospheric Environ., 35, 703-713, 2001.

Giering, R., Tangent Linear and Adjoint Biogeochemical Models, in Inverse Methods in Global Biogeochemical Cycles, edited by M.H. P. Kasibhatla, P. Rayner, N. Mahowald, R.G. Prinn, D.E. Hartley, pp. 33-48, American Geophysical Union, Washington, DC, 2000.

Gschwandtner, G., K. Gschwandtner, and K. Eldridge, Historic emissions of sulfur and nitrogen oxides in the United States from 1900 to 1980, volume I, Report EPA-600/7-85-009a. Washington: United States Environmental Protection Agency (U.S. EPA), 1985.

Hameed, S. and J. Dignon, Changes in the geographical distributions of global emissions of NO_x and SO_x from fossil fuel combustion between 1966 and 1980. Atmospheric Environment, 22, 441-449, 1988.

Houghton, J.T., M. Filho, B. Lim, K. Treanton, I. Mamaty, Y. Bonduki, D.J. Griggs, and B.A. Callander, Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Intergovenmental Panel For Climate Change, Paris, France, 1997.

Houweling, S., and H. Denier van der Gon, Estimation of Methane Emissions from Rice Fields Using Inverse Modeling, pp. 67-72, National Institute of Public Health and the Environment, Bilthoven, The Netherlands, 1997.

Houweling, S., T. Kaminski, F. Dentener, J. Lelieveld, and M. Heimann, Inverse Modeling of Methane Sources and Sinks Using the Adjoint of a Global Transport Model, J. Geophys. Res., 104 (D21), 26137-26160, 1999.

Houweling, S., F. Dentener, J. Lelieveld, B. Walter, and E. Dlugokencky, The Modeling of Tropospheric Methane: How Well Can Point Measurements be Reproduced by a Global Model?, J. Geophys. Res., 105 (D7), 8981-9002, 2000.

International Energy Agency (IEA), Energy statistics of OECD and non-OECD countries 1971-1992, Paris, France, 1994.

International Energy Agency (IEA). Key World Energy Statistics from the IEA, International Energy Agency, Paris, France, 2002a.

International Energy Agency (IEA), Energy Statistics of OECD countries, 1960-2000, Paris, France, 2002b.

International Energy Agency (IEA), Energy Statistics of non-OECD countries, 1971-2000, Paris, France, 2002c.

International Institute for Applied Systems Analysis (IIASA), RAINS-ASIA CD-ROM Version 7.52, 2001.

International Monetary Fund Staff, World Economic Output: Focus on Transition Economies, International Monetary Fund, Washington, DC, 2000.

IPCC, Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds), Cambridge University Press, U.K. and New York, NY, USA, 2001.

Johnson, N.D., M.T. Scholtz, and V. Cassaday, Methods Manual for Estimating Emissions of Common Air Contaminants from Canadian Sources, ORTECH International, Mississauga, Ont., Canada, 1991.

Kato, N., and H. Akimoto, Anthropogenic Emissions of SO_2 and NO_x in Asia: Emissions Inventories (plus errata), Atmos. Environ., 26A, 2997-3017, 1992.

Keeling, C.D., Global historical CO_2 emissions. In: BODEN, T.A., ed., Trends '93: A Compendium of Data on Global Change, ORNL/CDIAC-65. Oak Ridge Tenn.: Carbon Dioxide Information Analysis Center (CDIAC), pp. 501 – 504, 1994.

Klein Goldewijk, C.G.M. and J.J. Battjes, A hundred year (1890 – 1990) database for integrated environmental assessment (HYDE version 1.1). RIVM report 422514002. Bilthoven: National Institute of Public Health and the Environment (RIVM), 1997.

Klimont, Z., J. Cofala, W. Schopp, M. Amann, D.G. Streets, Y. Ichikawa, and S. Fujita, Projection of SO_2, NO_x, NH_3 and VOC emissions in East Asia up to 2030, Water, Air, and Soil Pollution, 130, 193-198, 2001.

Lefohn, A. S., J. D. Husar, and R. B. Husar, Estimating historical anthropogenic global sulfur emission patterns for the period 1850–1990, Atmospheric Environment, 33, 3435–3444, 1999.

Li, Y.-F., Global Population Distribution Database, United Nations Environment Programme under UNEP Sub-Project FP/1205-95-12, New York, NY, 1996.

Maddison, A., Monitoring the World Economy. Paris: Organization for Economic Co-operation and Development, 1994.

Marland, G., R.J. Andres, and T.A. Boden, Global, Regional, and National CO_2 Emissions, in Trends 93: a Compedium of Data on Global Change, edited by T.A. Boden, D.P. Kaiser, R.J. Sepanski, and F.W. Stow, pp. 505-584, Carbon Dioxide Information Analysis Center, Oak Ridge, TN, 1994.

Marland, G., A. Brenkert and J. Olivier, CO_2 From Fossil Fuel Burning: A Comparison of ORNL and EDGAR Estimates of National Emissions, Environ. Sci. and Technol., 2, 265-273, 1999.

Marland, G., T.A. Boden, and R. J. Andres. Global, Regional, and National Fossil Fuel CO_2 Emissions, In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A., 2002.

Moran, A., and J.E. Salt, International Greenhouse Gas Inventory Compilation Systems CORINAIR and IPCC, EU Directorate General XII Environment Programme, 1996.

Motor Vehicle Manufacturers Association of the United States, World Motor Vehicle Data, Motor Vehicle Manufacturers Association of the United States, Detroit, MI, 1998.

Murano, K., Y. Tonooka, and A. Kannari, Studies on the development of matrix for air pollutants emission and deposition and international cooperative field survey in East Asia, Report for global environmental research fund, Japan, (in Japanese), 2002.

Mylona, S., Sulfur dioxide emissions in Europe 1880– 1991 and their effect on sulphur concentrations and depositions, Tellus, Ser. B, 48, 662– 689, 1996.

Ohara, T., H. Akimoto, J. Kurokawa, K. Yamaji, and D.G. Streets, Development of emission inventories for anthropogenic sources in East, Southeast and South Asia, International workshop emissions of chemical species and aerosols into the atmosphere, June 19-21, Paris, France, 2001.

Olivier, J.G.J., Bouwman, A.F., Van der Maas, C.W.M., Berdowski, J.J.M., Veldt, C., Bloos, J.P.J., Visschedijk, A.J.H., Zandveld, P.Y.J. and J.L. Haverlag. Description of EDGAR Version 2.0: A set of global emission inventories of greenhouse gases and ozone depleting substances for all anthropogenic and most biogenic sources on a per country basis and on 1°x1^{o} grid. RIVM, Bilthoven, December 1996, RIVM report nr. 771060 002 / TNO-MEP report nr. R96/119, 1996.

Olivier, J.G.J, A.F. Bouwman, J.J.M. Berdowski, C. Veldt, J.P.J. Bloos, A.J.H. Visschedijk, C.W.M. van der Maas, P.Y.J. Zandveld. Sectoral emission inventories of greenhouse gases for 1990 on a per country basis as well as on 1° x 1°, Environmental Science & Policy, 2, 241-264, 1999a.

Olivier, J.G.J, Bloos, J.P.J., Berdowski, J.J.M., Visschedijk, A.J.H. and A.F. Bouwman. A 1990 global emission inventory of anthropogenic sources of carbon monoxide on 1°x1^{o} developed in the framework of EDGAR/GEIA, Chemosphere: Global Change Science, 1, 1-17, 1999b.

Olivier, J.G.J. and J. Bakker, Historical global emission trends of the Kyoto gases HFCs, PFCs and SF_6. Proceedings of *"Conference on SF_6 and the Environment: Emission Reduction Strategies"*, November 2-3, San Diego. EPA, Washington DC, USA, 2000. Conference Proceedings published at http://www.epa.gov/highgwp1/sf6/partner_resources/ proceedings.html

Olivier, J. Emission inventories of national sources, IGACtivities, 22, 5-9; December, 2000.

Olivier, J.G.J., J.J.M. Berdowski, J.A.H.W. Peters, J. Bakker, A.J.H. Visschedijk and J.P.J. Bloos, Applications of EDGAR. Including a description of EDGAR V3.0: reference database with trend data for 1970-1995, RIVM report 773301 001 / NRP report 410200 052, 2001.

Olivier, J.G.J. and J.J.M. Berdowski. Global emissions sources and sinks. In: Berdowski, J., Guicherit, R. and B.J. Heij (eds.) "*The Climate System*", pp. 33-78. A.A. Balkema Publishers/Swets & Zeitlinger Publishers, Lisse, The Netherlands, ISBN 90 5809 255 0, 2001.

Olivier, J.G.J. and J.A.H.W. Peters, Uncertainties in global, regional and national emission inventories. In: Van Ham, J., A.P.M. Baede, R. Guicherit and J.F.G.M. Williams-Jacobse (eds.):Non-CO2 greenhouse gases: scientific understanding, control options and policy aspects. Proceedings of the Third International Symposium, Maastricht, Netherlands, 21-23 January 2002, pp. 525-540. Millpress Science Publishers, Rotterdam. ISBN 90-77017-70-4, 2002.

Pechan, E.H. & Associates, Inc., Documentation for the Final 1999 National Emissions Inventory for Criteria Air Pollutants, Nonroad Sources, U.S.Environmental Protection Agency, Research Triangle Park, NC 27711, 2002.

Reddy, M.S. and C. Venkataraman, Inventory of aerosol and sulphur dioxide emissions from India: Part I - Fossil fuel combustion, Atmospheric Environ., 36, 677-697, 2002a.

Reddy, M.S. and C. Venkataraman, Inventory of aerosol and sulphur dioxide emissions from India. Part II – Biomass combustion, Atmospheric Environ., 36, 699-712, 2002b.

Saeger, M., J. Langstaff, R. Walters, L. Modica, D. Zimmerman, D. Fratt, D. Dulleba, R. Ryan, J. Demmy, W. Tax, D. Sprague, D. Mudgett, and A.S. Werner, The 1985 NAPAP Emissions Inventory (Version 2): Development of the Annual Data and Modelers' Tape, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1989.

SEPA, 1998 Reports on the State of the Environment in China. State Environment Protection Administration, Beijing, China, 1998.

Shareef, G.S., and L.A. Bravo, Air Emissions Species Manual - Volume I - Volatile Organic Compounds Species Profiles, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1993a.

Shareef, G.S., and L.A. Bravo, Air Emissions Species Manual - Volume II - Particulate Matter (PM) Species Profiles, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1993b.

Skjølsvik, K. O., A. B. Andersen, et al. Study of Greenhouse Gas Emissions from Ships (MEPC 45/8 Report to International Maritime Organization on the outcome of the IMO Study on Greenhouse Gas Emissions from Ships). Trondheim, Norway, MARINTEK Sintef Group, Carnegie Mellon University, Center for Economic Analysis, and Det Norske Veritas, 2000.

Stern, D., and R. Kaufmann, Estimates of global anthropogenic methane emissions 1860–1993. Chemosphere, 33, 159–176, 1995.

Streets, D.G., N.Y. Tsai, H. Akimoto, and K. Oka, Sulfur dioxide emissions in Asia in the period 1985-1997, Atmospheric Environ., 34, 4413-4424, 2000.
Streets, D.G., N.Y. Tsai, H. Akimoto, and K. Oka, Trends in emissions of acidifying species in Asia, 1985-1997, Water, Air, and Soil Pollution, 130, 187-192, 2001.

Tarrasón, L., and J. Schaug, Transboundary Acid Deposition in Europe, pp. 246, Norwegian Meteorological Institute, Oslo, Norway, 1999.

United Nations Economic Commission for Europe & Food and Agriculture Organisation of the United Nations (UN/ECE-FAO), Forest Fire Statistics 1993-1995, Timber Bulletin, Vol. XLIX, No. 4, ECE/TIM/BULL/49/4, United Nations, 1996.

United Nations Economic Commission for Europe & Food and Agriculture Organisation of the United Nations (UN/ECE-FAO), Forest Fire Statistics 1995-1997, United Nations, 1998.

United Nations Economic Commission for Europe, Procedure for Estimating and Reporting Emission Data Under the Convention on Long-Range Transboundary Air Pollution, United Nations Economic Commission for Europe, Geneva, Switzerland, 1997.

United Nations Economic Commission for Europe, Guidelines for estimating and reporting emission data Under the Convention on Long-Range Transboundary Air Pollution, United Nations Economic Commission for Europe, Geneva, Switzerland, 2002, EB.AIR/GE.1/2002/7 (http://www.unece.org/env/documents/2002/eb/ge1/eb.air.ge.1.2002.7.e.pdf), 2002.

United Nations Framework Convention on Climate Change, UNFCCC Guidelines on Reporting and Review, FCCC/CP/1999/7, Conference of the Parties, Bonn, Germany, 2000.

United Nations, 1999 Energy Statistics Yearbook, United Nations Department for Economic and Social Information and Policy Analysis, Statistics Division, New York, NY, 2002.

U.S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1985.

U.S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors (AP-42) Volume 1: Point and Area Sources, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1999.

U.S. Environmental Protection Agency, Office of Transportation and Air Quality, Assessment and Standards Division, User's Guide to MOBILE6.0: Mobile Source Emission Factor Model, Report No.: EPA420-R-02-001, 2002.

U.S. Geological Survey, Minerals Yearbook-2000, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA, 2002.

Van Aardenne, J.A., F. J. Dentener, J.G.J. Olivier, C.G.M. Klein Goldewijk and J. Lelieveld, A 1° x 1° resolution data set of historical anthropogenic trace gas emissions for the period 1890 – 1990. Global Biogeochemical Cycles, 15, 909-928, 2001.

Van Heyst, B.J., M.T. Scholtz, C.M. Benkovitz, A. Mubaraki, J.G.J. Olivier and J.M. Pacyna, 1990 Global Inventories of SO_x and NO_x on a 1° X 1° Latitude-Longitude Grid, in The Emission Inventory: Regional Strategies for the Future, Air and Waste Management Association, Raleigh, NC, 1999.

Várhelyi, G., Continental and Global Sulfur Budgets - I. Anthropogenic SO_2 Emissions, Atmos. Environ., 19, 1029-1040, 1985.

Vestreng, V. and H. Klein, Emission data reported to UNECE/EMEP: Quality assurance and trend analysis – Presentation of WebDab, EMEP/MSC-W Note 1/2002, 2002.

Wagner, J., R.A. Walters, L.J. Maiocco, and D.R. Neal, Development of the 1980 NAPAP Emissions Inventory, U.S. Environmental Protection Agency, Washington, DC, 1986.

Woodruff, S.D., et al., Comprehensive Ocean-Atmosphere Data Set (COADS) Release 1a: 1980-92. Earth System Monitor, 4(1), 1993.

World Bank, World Tables, Washington, DC, 1993.

World Bank Group, Global Economic Prospects 2001, pp. 180, World Bank, Washington, DC, 2000.

World Energy Council, Survey of Energy Resources, World Energy Council, London, UK, 1998.

World Resources Institute, World Resources 2000-2001, pp. 400, World Resources Institute, Washington, DC, 2000.

Xue, Z., Z. Yang, X. Zhao, F. Chai, and W. Wang, Distribution of SO_2 and NO_x emissions in China, 1995, Proceeding of the 6th International Conference on Atmospheric Sciences and Applications to Air Quality, Beijing, China, November 3-5, 1998.

Yamaji, K., T. Ohara, and H. Akimoto, Development of emission inventory of methane from livestock in South, Southeast and East Asia, Atmos. Enviorn. (to be published, 2003)

Yan X., T. Ohara, and H. Akimoto, Development of region-specific emission factors and estimation of methane emission from rice field in East, Southeast and south Asian countries, Global Change Biology, 9, 237-254, 2003.

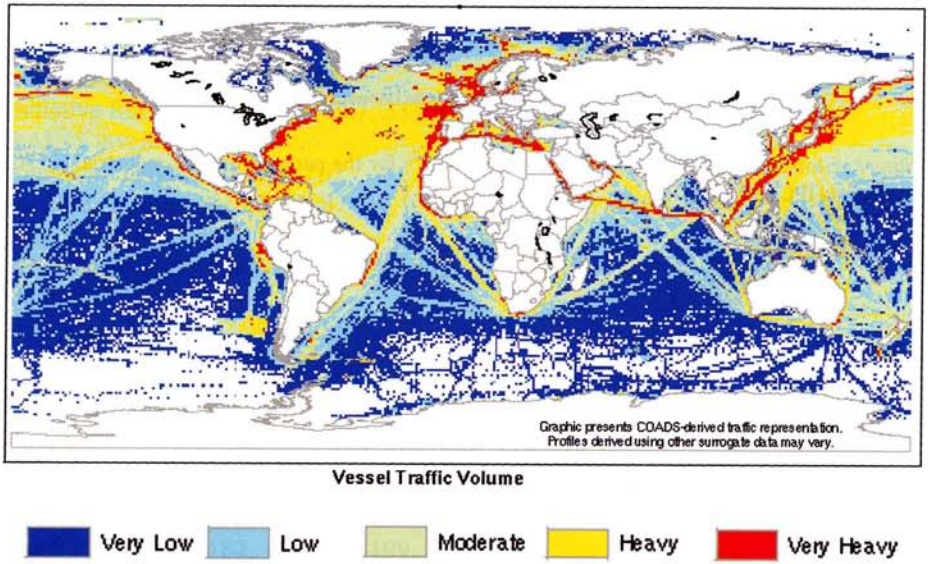
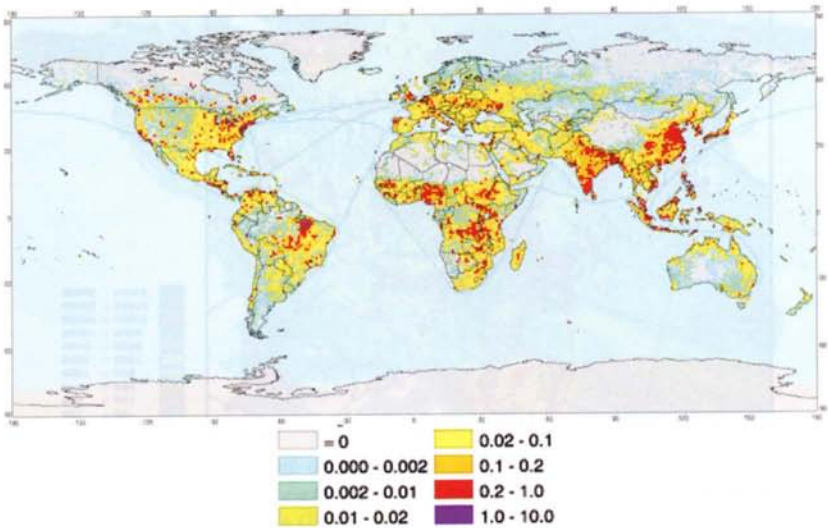


Plate 3. International ship traffic for 1990 (adapted from Corbett et al., 1999 and Skjølsvik et al. 2000)



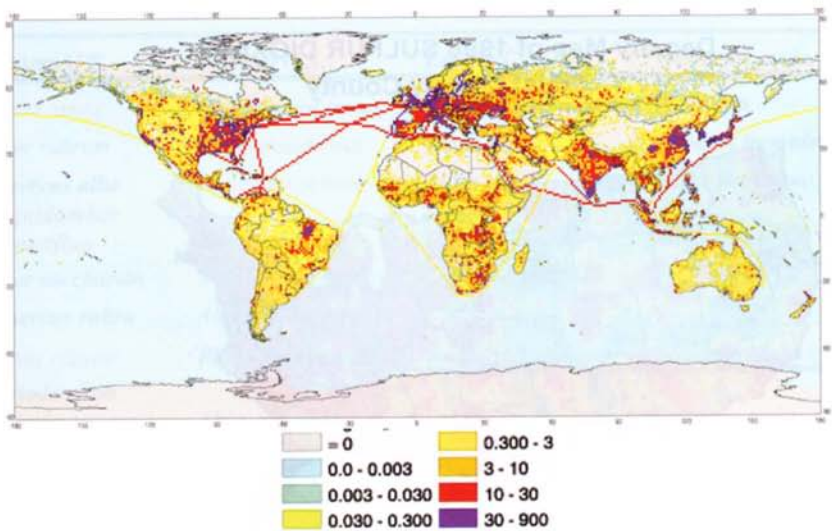


Plate 4: Global distribution of NO_x (top) and CO (bottom) anthropogenic emissions in 1995. Source: EDGAR 3.2

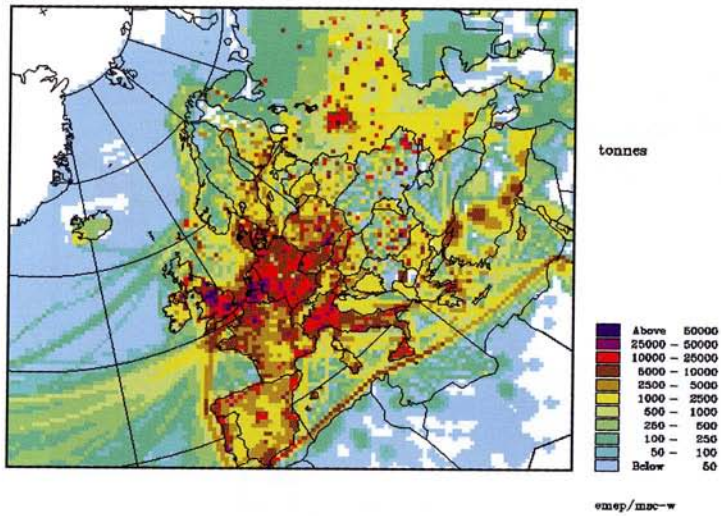


Plate 5. European emissions of NO_x in 1995 at 50 km grid resolution (Mg as NO_2)

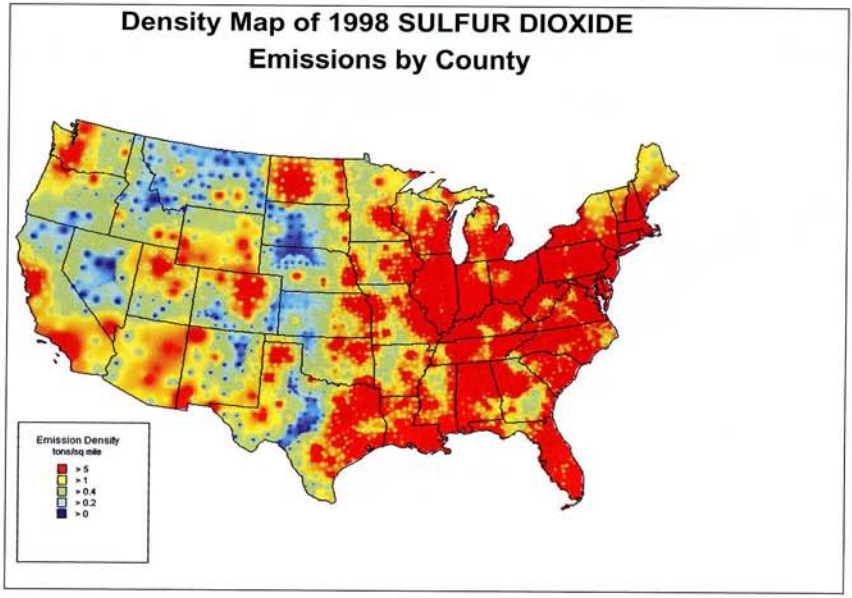


Plate 6. Emissions of SO_2 in the United Stated in 1998 (short tons/mile^2). From EPA web site http://www.epa.gov/ttn/chief/trends.