Chapter 4
Emissions Inventories and Projections for Assessing Hemispheric orIntercontinental Transport

4.1 Introduction

Gridded global, regional, and national emission estimates exist for many of the pollutants that are important for assessing the hemispheric transport of air pollution (SO_2, NO_x, NMVOC, NH_3, CH_4, OC, BC, PM, and CO). Some of these are publicly available, whereas others are used by individual research groups or government agencies to study specific aspects of emissions or atmospheric processes. Most inventories are developed by combining emission factors, in units of mass of emissions per unit of activity, with activity levels or proxies thereof. The quality of emission inventories varies widely, however, and is difficult to assess objectively. For developed countries, the inventories for some pollutants from some sectors are viewed to be of high quality, as they have been crosschecked by field studies and laboratory tests and through air quality modeling. Examples of high-quality inventories would be the SO_2 emissions from power generation in North America and Europe. For other pollutants and sectors, the quality of inventories may be considerably lower. In developing and newly industrializing countries, the quality of emission inventories is generally poor, due to a lack of actual emissions measurements and intensive ambient observations, incompleteness of the activity data, and absence of test-based emission factors. A shorter history of inventory development in these regions also means a lack of expertise and institutions.

Major uncertainties in emission inventories are associated with inadequate knowledge of open biomass burning (forest fires, agriculture waste burning), biofuel use (heating and cooking), artisanal industry, residential combustion of coal, and agricultural production systems. These propagate into higher uncertainties in emissions for the pollutants that are mainly associated with these activities, such as CO, PM, OC, BC, and individual VOC species. Due to a lack of comprehensive activity data, there is a tendency to underestimate the emissions of these pollutants. Also, there are some source types that are relevant for the intercontinental transport of air pollution but less relevant for local air quality management, including marine (though ship emissions are becoming of major importance in some European cities) and aviation emissions, natural emissions (including various methane sources, soil and lightning NO_x, volcanoes, windblown dust), agricultural emissions, and biomass burning in remote areas. These may need greater attention from TF HTAP than they have received thus far from national governments. In recent years, some new tools have become available to address the uncertainties in emission inventories, including direct (forward) and inverse modeling of air quality observations (from ground-based monitors, aircraft, or satellites) and laboratory tests of combustion and similar processes. Bringing together the scientific communities in these areas could be a valuable function of TF HTAP.

This chapter first reviews the status of present-day inventories at global, regional, and national scales. Next it identifies sources of uncertainty, methods of quantifying uncertainty, and pathways to reduce uncertainties by making use of new satellite and modeling capabilities. Third, methods to project future emissions are presented, together with examples of what has been achieved so far. The major sources of natural emissions are introduced. Finally, the chapter discusses opportunities to harmonize the presently available inventories and makes recommendations to TF HTAP on how to make progress in improving the emission inventories that are the foundation of hemispheric transport determinations.

4.2 Present-day emission inventories

4.2.1Global inventories and databases

Currently available global emission inventories differ in the compounds included, emission sources covered, and spatial and temporal resolution. This is often related to the different purposes for which they were developed. Most inventories are based on an emission factor approach. Emission factors are identified for specific sectors, considering fuels, production or combustion technology, and presence and effectiveness of abatement. Some inventories explicitly define control measures and technologies, while in others emission factors are derived from reported or measured emission data (implied factors). Table 4-1 summarizes relevant global emission inventories that can be used for assessing intercontinental transport and hemispheric pollution. Some natural sources (wildfires, soil and lightning NO_x, etc.) may be included in some of these inventories, but the emphasis is usually on anthropogenic emissions.

Table 4-1 Overview of global, gridded anthropogenic emission inventories with compounds included that are relevant for studies of hemispheric transport of air pollutants.

	Individual studies	**Project-based calculations**	**Emission databases**	**Inventory compilations**
CO	-	RETRO, QUANTIFY, POET	EDGAR, RAINS	GEIA
NH_3	Bouwman et al. (1997)	-	EDGAR(v2)	GEIA
NO_x	-	RETRO, QUANTIFY, POET,	EDGAR, RAINS	GEIA
NMVOC (total)	-	RETRO, QUANTIFY, POET	EDGAR	GEIA
NMVOC (speciated)	-	RETRO, QUANTIFY, POET	EDGAR(v2)	GEIA
SO_2	Stern (2005)	QUANTIFY	EDGAR, RAINS	GEIA, AEROCOM
BC	Bond et al. (2004)	QUANTIFY	EDGAR, RAINS	GEIA, AEROCOM
OC	Bond et al. (2004)	QUANTIFY	EDGAR, RAINS	AEROCOM
CH_4	-	QUANTIFY	RAINS	UNFCCC

All of the global inventories draw heavily on individual studies of a particular pollutant or source type that, in the ideal case, apply a consistent methodology across all included regions. Global emissions of a number of species have been studied in such special inventories, e.g., NH_3 [*Bouwman et al.*, 1997], BC and OC [*Bond et al.*, 2004], SO_2 [*Stern*, 2005], as well as particular source types, e.g., biomass burning [*van der Werf et al.*, 2003] and shipping [*Corbett et al.*, 1999]. However, special inventories are prepared for different years, often make use of different activity data sources and vary in level of detail. For some pollutants, there are no global studies of this type, e.g., particulate matter. Consequently, there are a number of projects where compilations of specific inventories, enhanced with regional work and attempts to draw on consistent activity databases, have led to the development of large-scale databases for use in global modeling studies.

EDGAR (Emission Database for Global Atmospheric Research) presents global emissions of air pollutants and greenhouse gases from anthropogenic and biomass burning sources distributed by country and on a 1° × 1° degree grid using a variety of proxy and actual spatial distributions [*Olivier et al.*, 1996]. Emissions are calculated using an emission factor approach. EDGAR emissions have been used as the basis of various other inventory projects (e.g., GEIA, POET, QUANTIFY). The latest dataset is for the year 2000 [*Olivier et al.*, 2005; *van Aardenne et al.*, 2005].

The **RAINS** integrated assessment model has been developed by IIASA. Although largely used in regional studies for Europe [*Amann et al.*, 2004; *Kupiainen and Klimont*, 2007] and Asia [*Cofala et al.*, 2004; *Klimont et al.*, 2001], recently it has been extended to estimate global emissions for several compounds for anthropogenic sources [*Cofala et al.*, 2007]. Emissions are calculated for the period 1990-2030 by country or larger region using an emission factor approach, where penetration of abatement technologies is explicitly included. Recently, emissions have been allocated to 1° × 1° grid cells based on the EDGAR methodology [*Olivier et al.*, 2005].

To study precursors of ozone and their effects in the troposphere, the **POET** project developed an emission inventory that included anthropogenic and biomass burning emissions [*Granier et al.*, 2005]. For anthropogenic sources, emissions were estimated for 1990, 1995 and 1997 relying on EDGARv3 data, while biomass burning emissions were calculated for 2000 based on satellite fire counts data and vegetation maps [*Tansey et al.*, 2004a,b].

For analysis of the tropospheric composition over the past 40 years, the **RETRO** project developed an anthropogenic and biomass burning emission inventory covering the period 1960-2000 with monthly emissions of CO, NO_x, and NMVOC on a 0.5° × 0.5° grid [*Schultz et al.*, 2007]. Anthropogenic emissions are calculated using **TEAM** (the TNO Emission Assessment Model) [*Pulles et al.*, 2005], based on an emission factor approach with explicit assumptions about technologies applied.

To quantify the climate impact of global and European transport systems, the **QUANTIFY** project currently develops global gridded emission inventories and scenarios out to 2100 of anthropogenic emissions of greenhouse gases and air pollutants. In particular, transport (road, shipping and aviation) emissions are calculated, and non-transport emissions are taken from the EDGAR 2000 dataset. The results are not yet published, but datasets may be available on request (http://www.pa.op.dlr.de/quantify/).

Although not providing the most recent emissions data, the **GEIA** project has compiled global emission inventories for many of the pollutants of interest on a 1° × 1° grid, by assembling material from a variety of databases (e.g., EDGAR), studies and projects. Dentener et al. [2006] compiled global emission sets for 2000 for the **AEROCOM** project to study aerosols and aerosol precursors. Data originate from various sources, e.g., anthropogenic emissions of BC and POM [*Bond et al.*, 2004], SO_2 [*Cofala et al.*, 2006], international shipping and spatial (1° × 1° grid) distribution patterns from EDGAR [*Olivier et al.*, 2005], and biomass burning from the **GFED** (Global Fire Emissions Database) [*van der Werf et al.*, 2003].

The relative importance for global emissions of different sectors and fuel types is presented in Table 4-2. The contributions shown in this table can be markedly different, however, for individual countries and regions. The estimates are based on EDGAR FT2000 [*Olivier et al.*, 2005; *Bond et al.*, 2004], EDGARv2 [*Olivier et al.*, 1996], and Bouwman et al. [1997].

Table 4-2 Relative importance of different sectors to global emissions (% of total emissions).

Species	Large stationary combustion		Small stationary combustion		Transport		Industrial processes	Agriculture	Waste	Biomass Burning
	Fossil fuel	Biofuel	Fossil fuel	Biofuel	Road	Non-road				
CO	2	1	3	24	19	1	4	0	0	46
NH_3	0	0	0	3	0	0	1	82	6	8
NO_x	28	1	2	5	22	13	5	0	0	23
NMVOC	23[a]	2	1	16	20	3	16	0	2	17
SO_2	62	0	5	2	2	6	19	0	0	2
BC	3	2	15	22	14	5	0	0	0	38
OC	1	3	2	21	4	0	0	0	0	69
CH_4	30	0	1	4	0	0	0	40	18	6

[a] includes exploration of oil and gas

An illustration of the geographical distribution of global emissions is shown in Figure 4-1, which presents gridded emissions of CO and NO_x from anthropogenic sources (excluding aviation) and biomass burning.

4.2.2Regional and national inventories and databases

National and regional inventories are developed as part of research projects or as official data for regulatory purposes or international reporting. Similarly to global work, special inventories play an important role in compiling regional emission databases. The inventory methods are similar to those used in the global datasets, but typically contain more information on plant measurements and individual facilities. While these assessments cannot be described here in any detail, some important ones need to be mentioned. Also, the scope of such studies has been different among the continents. While in Europe and North America more sector-specific studies have been produced (e.g., transport, power, and agriculture), in Asia more pollutant-oriented work has been published (e.g., studies of SO_2 and NO_x). In Europe and the United States, emission inventory guidelines have been developed, such as the **EMEP/CORINAIR** Guidebook (http://reports.eea.europa.eu/EMEPCORINAIR4/en/page002.html) and U.S. EPA's **AP-42** database (http://www.epa.gov/ttn/chief/ap42/index.html), which have become part of legislation or regulations asking for annual national emission estimates for regulated pollutants.

The **EMEP** database is the main European dataset (http://www.emep.int). It includes a range of pollutants (no GHG, BC, or OC) for past, present and future years (until 2020) and is distributed both by source and on a 50 × 50 km grid. The origin of the data is official national submissions from Parties to the CLRTAP. Where submissions are missing or incomplete, gaps are filled by EMEP [*Vestreng et al.*, 2006].

The **RAINS** model has been independently developed for Europe [*Amann et al.*, 2004; *Kupiainen and Klimont*, 2007] and Asia [*Cofala et al.*, 2004; *Klimont et al.*, 2001] and contains detailed sectoral emission assessments for countries (Europe) and for countries, states, and provinces (Asia). The RAINS model calculates emissions of SO_2, NO_x, NH_3, NMVOC, PM, BC, OC, CO, CO_2, and CH_4 for the period 1990-2030, based on an emission factor approach, and its databases for Europe have been subject to

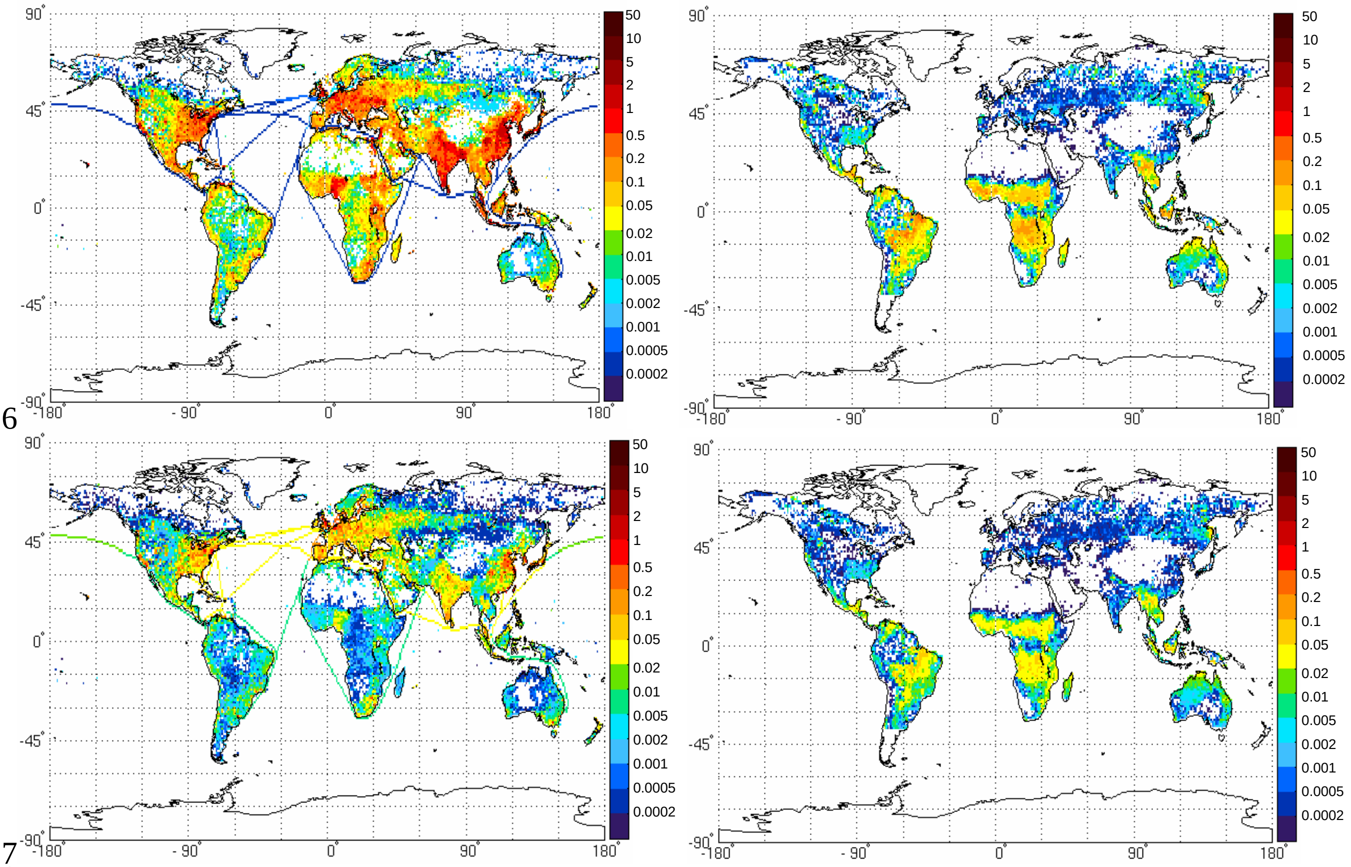


Figure 4-1. Global emissions of carbon monoxide (top panels) and nitrogen oxides (bottom panels) from anthropogenic sources (left panels) and biomass burning (right panels), gridded at 1° × 1° resolution, taken from the EDGARv32FT2000 dataset (units 10^9 kg m^{-2} s^{-1}).

review by national experts. The results for historical years have been found to be in good agreement with the EMEP database and several special inventories.

The **CEPMEIP** project [*CEPMEIP*, 2002] developed European PM emissions for 1995. The data and results are available from the dedicated web site (http://www.air.sk/tno/cepmeip/). An updated PM inventory (by country) for Europe for the year 2000, building on the CEPMEIP project, was completed in 2006 and results are expected to be available in the near future.

The European Pollutant Emission Register, **EPER** (http://eper.ec.europa.eu), established in 2000, includes emissions to air and water. The database contains approximately 9,200 industrial facilities in the EU15, Norway and Hungary for 2001 and approximately 12,000 facilities in the EU25 and Norway for the year 2004. EPER will be developed to include more facilities in the future.

The United States, Canada and Mexico all prepare and maintain emission inventories. The U.S. National Emission Inventory (**NEI**) (http://www.epa.gov/ttn/chief/index.html) includes data on all criteria pollutants, important precursors and hazardous air pollutants by detailed source categories. Data are based on state, local and tribal submittals for point sources, supplemented by EPA analysis for area sources. Updated versions of the NEI are released every three years, with 1999 and 2002 being the latest versions. A helpful summary of North American emission inventories can be found in a recent **NARSTO** assessment (NARSTO, 2005).

Several regional emission inventory tools are now available for Asia, including the RAINS-Asia model referred to above, the NASA **TRACE-P** inventory [*Streets et al.*, 2003], and the Japanese Regional Emission Inventory in Asia (**REAS**) [*Ohara et al.*, 2007]. REAS presents emissions for several pollutants for the period 1980-2020. For some Asian countries, there are inventories available of similar quality to those in Europe and North America—particularly Japan, South Korea, and Taiwan. Elsewhere, inventories are available but based on less stringent requirements and not fully verified (China, India, Thailand, etc.). For the rest of Asia, national inventories are weak or non-existent.

For the rest of the northern hemisphere, information from local inventories is seriously lacking (Central Asia, the Russian Far East, the Middle East, and relevant parts of Africa and South and Central America). Emission estimates for these regions tend to be focused on specific cities where air quality problems are known to exist. Though emissions tend to be low in many of these regions, recent energy-related activities like oil and gas extraction are growing fast and may make them more important in the future.

Within Europe and North America, several countries have established emission inventory programs with ongoing reporting and updating activities, primarily as a response to requirements in international and national legislation. Japan has established a similar emission inventory program. Where such programs have become well-established institutions, they provide regular, consistent and transparent emission inventories that are often of great value to compilers of regional and global inventories. Comparable institutions do not exist yet in most of the rest of the world.

4.3 Uncertainties and verification of present-day emission inventories

An uncertainty estimate is one of the quality indicators of an inventory and can be used to prioritise efforts to improve the inventory. Verification has been defined as *the collection of activities and procedures conducted during the planning and development, or after the completion of an inventory that can be used to establish its reliability for the intended application of the inventory* [*IPCC*, 2006]. Verification methods include comparisons of different inventories, comparisons of results of alternative methods and comparisons with atmospheric measurements. These methods are complementary.

4.3.1 Quantification of uncertainties

Statistical approaches to estimate uncertainties in emission inventory levels and trends have been developed at large scale by the IPCC (2006) and in more specific applications [e.g., *Frey and Zheng,* 2002]. Two approaches are typically used: simple error propagation and Monte Carlo simulations. The main challenges in estimating inventory uncertainties are, however, uncertainty in the input data and developing methods to quantify systematic errors. For most inventory applications the random component of an uncertainty estimate will be small compared to the systematic component. The IPCC [2006] lists the following sources of uncertainties to consider: lack of completeness, inventory model (estimation equation), lack of data, lack of representativeness of data, statistical random sampling error, measurement error, misreporting or misclassification, and missing data. Systematic expert judgments can be used to complement other sources of information on uncertainties. The usual metric for expressing uncertainty estimates is two standard deviations as a percentage of the mean.

4.3.2Intersection of inventories with observations and modeling

Since 2000, there have been a number of new analytical tools applied to the elucidation of emissions emanating from sources in the northern hemisphere. Techniques include improved forward modeling and inverse modeling, making use of improved ground-station monitoring networks, and aircraft observations during large-scale field campaigns. Also, a new generation of satellites has provided trends based on column data that have been compared with emission trends. More often than not, the observation-based methods have suggested that emission estimates obtained from inventories, particularly in developing and newly industrializing countries, are too low. Bergamaschi et al. [2000] were the first to apply inverse modeling techniques to CO, finding that their estimate of the CO source strength in the northern hemisphere (~800 Tg CO/yr) was considerably larger than inventory-based estimates of 550 Tg CO/yr [*IPCC*, 1995] and the EDGAR value of 478 Tg CO/yr [*Olivier et al.*, 1996]. Since then there have been many more inverse modeling studies, which are discussed in greater depth in Chapter 6. Streets et al. [2006] reconciled inventory and inverse modeling estimates of China's CO emissions following the NASA TRACE-P mission and subsequent data evaluation studies [*Kasibhatla et al.*, 2002; *Palmer et al.*, 2003; *Heald et al.*, 2004]. Other recent studies include Müller and Stavrakou [2005] on CO and NO_x and Meirink et al. [2006] on CH_4. Similarly, there are an ever-growing number of satellite-based studies of emission trends, of which Richter et al. [2005] on China's NO_x emission trends was the ground-breaking work. The use of satellite observations to inform emission inventories is discussed further in section 3.5.1. From the perspective of improving emission inventories, it is clear that there are potentially large benefits and opportunities to be gained if emission inventory compilers can work together with the atmospheric science community to identify deficiencies in inventory estimates.

4.3.3Important and uncertain sources

Uncertainties in inventories will vary by region, source, pollutant and inventory year. Uncertainty estimates for all world regions are not available. Generally it is expected that regions with the longest experience in compiling inventories and with a well developed statistical system (e.g., Western Europe, North America, and Japan) compile inventories with lower uncertainties than other regions.

The primary reasons for differences in uncertainties between sources are (i) activity statistics are missing or weak; (ii) emission factors and technologies are known better for some sources than for others; and (iii) the estimate depends on natural and variable factors such as temperature and precipitation. Usually, emissions related to the household sector, agriculture, and waste are more uncertain than for transportation and large industrial stationary sources. Natural sources and semi-natural sources (e.g., forest fires) are more uncertain than anthropogenic sources.

Uncertainties for individual pollutants differ also with the level of experience of compiling an inventory, and these uncertainties typically can be reduced over time. SO_2 inventories have a long history in Europe and North America and are considered relatively reliable in those regions. For other world regions, inadequate information about the sulphur content of fuels and sulphur removal efficiencies may add to the uncertainty. NO_x inventories are generally regarded as less certain than SO_2 inventories, while NMVOC and CO inventories carry high uncertainties. Due to the short experience in compiling PM, BC, and OC inventories and the lack of data on the distribution of technology types in key regions, these are even more uncertain. BC and OC inventories have uncertainty ranges of -25 % to a factor of two (higher for open burning) (Bond et al., 2004). Typical reported ranges of uncertainty estimates for Europe are: SO_2: ±5%, NO_x: ±14%, NMVOC: 10-39% and CO: ±32% [*EMEP*, 2006]. The TRACE-P inventory [*Streets et al.*, 2003] estimated uncertainties in Asian emissions that ranged from ±16% for SO_2 and ±37% for NO_x to more than a factor of four for BC and OC. Within Asia, there was wide variation among countries and regions, with emission uncertainties in Japan being similar to those in Europe, and emissions in South Asia having high uncertainty.

4.4 Projection of future emissions

The development of emission projections typically requires assumptions about economic growth, population, and the emission characteristics of production technologies. These are building blocks for the development of more detailed sets of assumptions and parameters, such as energy use projections, livestock developments, production of goods, changes in environmental legislation leading to different emission factors over time, etc. To consider changes in the spatial distribution of emissions, additional factors may need to be projected, e.g., the pace of economic and demographic development in the considered regions (at sub-national level).

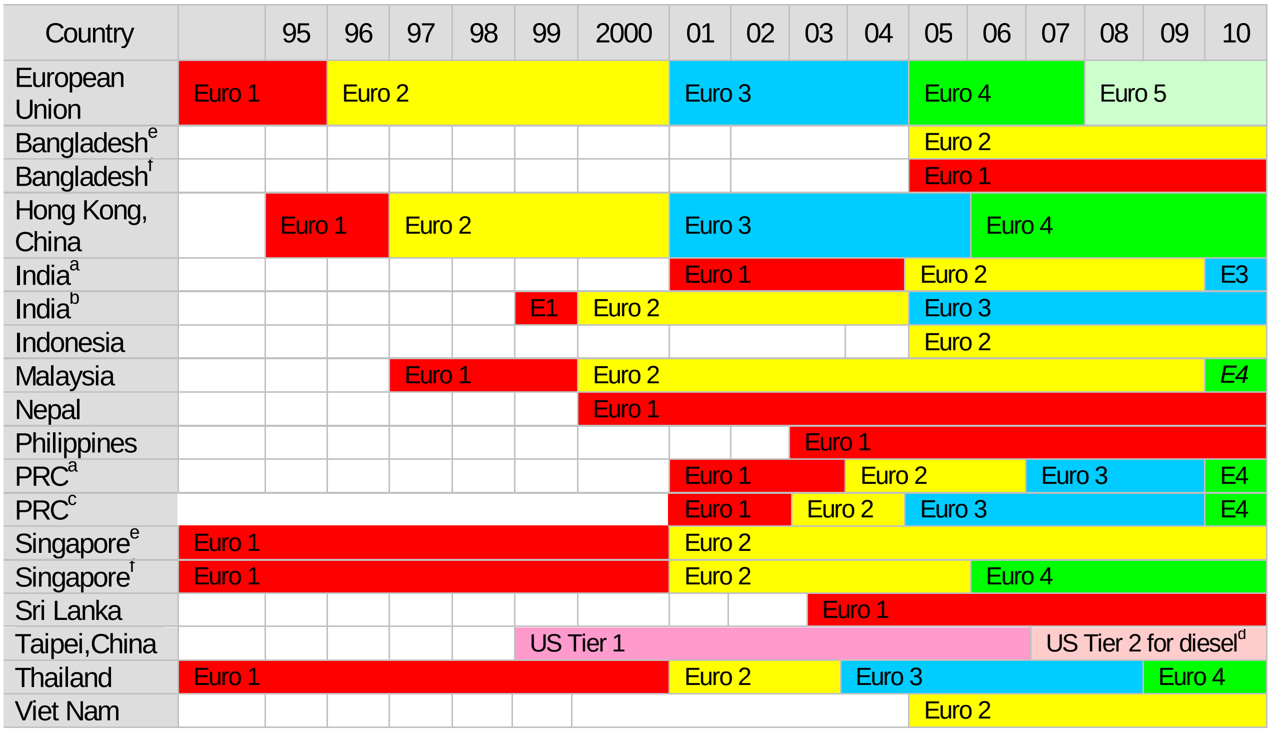
4.4.1 Driving forces

The most important factors determining future emission levels are activity, level of technology development, and penetration of abatement measures. Activity changes are strongly linked to economic growth, population growth, and energy growth (see Section 4.4.3), but they are also dependent on the geo-political situation, trade agreements, level of subsidies, labour costs, etc. While production technology improvements (with respect to emission level) are also related to economic growth, a far more important factor is environmental legislation. The latter can be a key factor in determining the penetration of abatement measures and consequently the apparent emission factors. As one example, Figure 4-2 shows the varying stages of automobile emission restrictions in Asian countries, compared to the stage of application in the European Union. Traditionally, national legislation drove the installation of control technology, but in some regions international (regional or global) agreements have become the key drivers. Examples include the Kyoto Protocol, UNECE CLRTAP Protocols, and EU Directives. At national level, the economic projections are frequently updated, as are as some key activity factors, e.g., population and energy use. Regional or global projections of drivers are updated less frequently, and such work is often driven by policy needs, e.g., the global SRES scenarios, EU energy or agricultural projections, and the work of international agencies such as IEA, OECD, and FAO.

4.4.2 Methods

There are two principal categories of approaches used to develop views of future emissions:

- Projections of activities that generate emissions (e.g., energy use, fertilizer use, livestock, and production of goods), together with production technology development and penetration of abatement measures, based on existing and forthcoming legislation and autonomous improvement of technology over time, e.g., Streets et al. [2004].
- Projections of proxies, such as population or economic growth, to change emissions over time, assuming little or no change in unit emissions; a possible enhancement to this approach is to use elasticity against emissions to account for improvements in production technology or possible increases in penetration of abatement measures, but this approach requires much historical data.



Country		95	96	97	98	99	2000	01	02	03	04	05	06	07	08	09	10
European Union	Euro 1		Euro 2					Euro 3				Euro 4			Euro 5		
Bangladesh[e]												Euro 2					
Bangladesh[f]												Euro 1					
Hong Kong, China		Euro 1		Euro 2				Euro 3					Euro 4				
India[a]								Euro 1				Euro 2					E3
India[b]						E1	Euro 2					Euro 3					
Indonesia												Euro 2					
Malaysia				Euro 1			Euro 2										*E4*
Nepal							Euro 1										
Philippines										Euro 1							
PRC[a]								Euro 1			Euro 2			Euro 3			E4
PRC[c]								Euro 1		Euro 2		Euro 3					E4
Singapore[e]	Euro 1							Euro 2									
Singapore[f]	Euro 1							Euro 2					Euro 4				
Sri Lanka										Euro 1							
Taipei,China						US Tier 1								US Tier 2 for diesel[d]			
Thailand	Euro 1							Euro 2			Euro 3					Euro 4	
Viet Nam												Euro 2					

[a] Entire country

[b] Delhi and other cities; Euro 2 introduced in Mumbai, Kolkata and Chennai in 2001; Euro 2 in Bangalore, Hyderabad, Khampur, Pune and Ahmedabad in 2003, Euro 3 to be introduced in Delhi, Mumbai, Kolkata, Chennai, Bangalore, Hyderabad and Ahmedabad in 2005

[c] Beijing and Shanghai

[d] Gasoline vehicles under consideration

[e] for gasoline vehicles

[f] for diesel vehicles

Figure 4-2. Level of automobile emission limits in Asian countries, compared with the European Union. Source: Clean Air Initiative for Asian cities

It is important to carefully consider consistency when compiling projections from different sets of data where the underlying methods may differ or the assumptions are not well known or documented.

4.4.3 Future emission inventories

There are a number of key studies and papers that provide important information on future emission levels, globally and in certain world regions and countries.

The **IPCC SRES** (Special Report on Emission Scenarios) scenarios [*Nakicenovic et al.*, 2000] are well-known and reflect a large, global, long-term effort, and so cannot be updated very often (the last scenarios were developed in the mid-1990s). Although the SRES scenarios assume improvements in production technology, they do not include some of the expected changes in the future penetration of abatement measures (the impacts of existing legislation); also, they do not include some of the aerosols and PM species and are available only for aggregated regions rather than countries.

There are a number of global projections that have been published in the peer-reviewed literature. For example, Streets et al. [2004] developed a forecast of future BC and OC emissions, drawing on SRES activity data and incorporating the evolution of production and control technology, specifically for non-industrial sectors. Cofala et al. [2007] developed global projections for air pollutants (excluding NMVOC, NH_3, and PM) and methane out to 2030. The spatial resolution varies by continent. A longer-term projection (up to 2100) for BC and OC but also taking into account CO_2 abatement options and policies was prepared by Rao et al. [2005]; the activity data draw on the SRES scenarios. As part of its Clean Air Interstate Rule (CAIR), the U.S. EPA has developed near-term emission forecasts of SO_2 and NO_x (http://www.epa.gov/cair/index.html).

For Europe, the RAINS model includes projections of air pollutants and greenhouse gases out to 2030, developed in consultation with national experts [*Amann et al.*, 2006a], and the EMEP database contains official projections (up to 2010) for several European countries. The EMEP database, however, often lacks the supporting data that would allow for reconstruction and verification of emissions. For Asia, several studies looked at particular pollutants, while the RAINS-Asia model has been used to prepare a consistent set of projections drawing on national energy data and international studies for other drivers. The work on global projections [*Cofala et al.*, 2007] includes updates for Asia (reflecting changes in legislation) and new projections for Russia. At global scale and for many regions in the Northern Hemisphere, projections of size-resolved and species-resolved PM have not yet been developed. Figure 4-3 presents examples of SO_2 and NO_x emission projections out to 2030 for OECD countries, Asia, and the rest of the world. Also shown are trends in three of the main driving forces of emissions: population, GDP, and energy use.

4.5 Natural emissions

Natural sources of atmospheric gases and particles include living and dead organisms, soil, lightning, and volcanoes. Natural emissions occur in the absence of people, but human activities can substantially alter these emissions. Methods have been developed for estimating global emissions of trace gases and particles from all major natural sources, including plant foliage VOC (Guenther et al., 2006), mineral dust [*Mahowald et al.*, 2006], volcanic SO_2 [*Andres and Kasgnoc*, 1998], lightning NO_x [*Price et al.*, 1997], soil NO_x [*Lee et al.*, 1997], wetlands methane [*Fung et al.*, 1991], and wildfires [*van der Werf et al.*, 2003]. The resolutions of these models range from hourly and 1 km × 1 km for plant foliage VOC to monthly and 1° × 1° for wetlands methane. The uncertainties associated with natural emissions are substantial and are highly dependent on the spatial and temporal scales considered. For example, the annual global isoprene emission is known to within a factor of two, but the uncertainty associated with the isoprene emission at a particular hour and location can exceed a factor of five [*Guenther et al.*, 2006]. In addition, uncertainties vary greatly for the various compounds emitted from vegetation foliage and wildfires. For example, the uncertainties associated with emissions of sesquiterpenes from foliage and NH_3 from wildfires are much higher than those associated with isoprene from foliage and CO_2 from fires.

A high resolution (10 km ×10 km) inventory of NO_x, SO_2, NH_3, PM, NMVOC, CH_4, CO, and DMS emissions from natural sources in Europe will be completed in 2007 (**NATAIR,** http://natair.ier.uni-stuttgart.de). Emission sources included as “natural” comprise vegetation (especially forests, forest and agricultural soils), primary biological aerosol particles, wild animals, humans, anoxic soil processes in wetlands, macro- and micro-seepages from geothermal and non-geothermal sources, wind-blown dust and Saharan dust, volcanoes and lightning. Emissions from pets, biomass burning and forest fires are also dealt with, even though they are often considered to be anthropogenic activities. The methodology developed to estimate emissions from these sources will be used to update the EMEP/CORINAIR Guidebook.

Uncertainty assessments of natural emission sources have focused on comparisons of available input databases [e.g., *Guenther et al.*, 2006; *Ito and Penner*, 2004; *Hoelzmann et al.*, 2004]. The uncertainties associated with emission factors and emission algorithms are more difficult to quantify. Comparisons of different emission estimates for any of these sources tend to agree within about a factor of two on annual global scales. However, the models are generally based on at least some of the same emissions data and

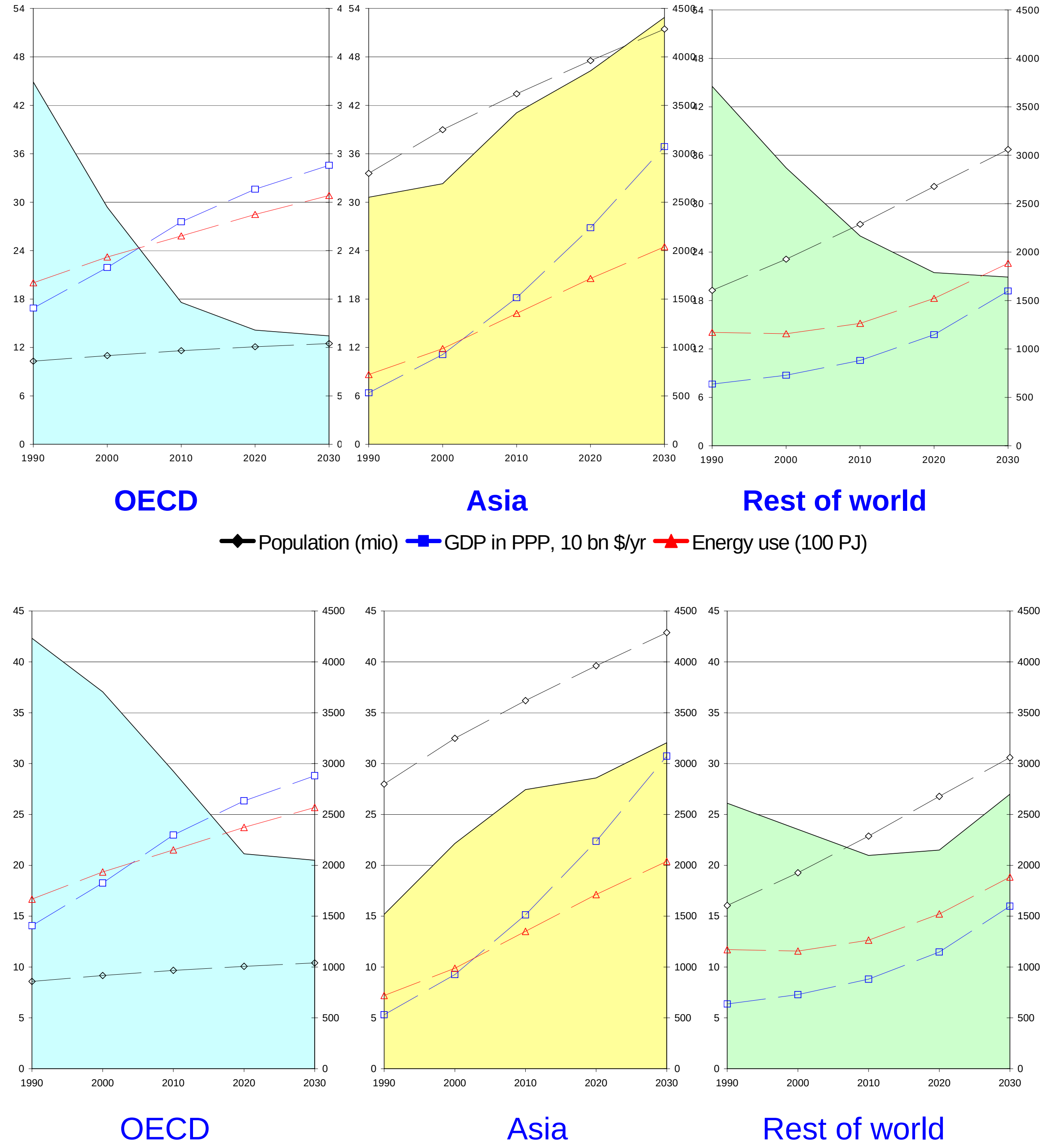


Figure 4-3 Projections of emissions of SO_2 (upper frames) and NO_x (lower frames) and their major driving forces in three world regions [*Amann et al.*, 2006b].

so are not independent estimates. Global satellite observations are beginning to provide a valuable tool for assessing emissions of, among others: foliar isoprene [*Shim et al.*, 2005], wildfires [*Pfister et al.*, 2005], lightning [*Boersma et al.*, 2005; *Martin et al.*, 2007], methane [*Frankenberg et al.*, 2005], and dust [*Mahowald et al.*, 2003]. These observations are valuable both for providing some confidence in natural emission estimates and for indicating regions and seasons of major discrepancies.

As estimates of present-day natural emissions have improved, research efforts have focused more on how these emissions will respond to climate and landcover change. Natural emissions of mineral dust, wetland methane, foliar VOC, and wildfires are all very sensitive to changes in landcover (e.g. vegetation type and density) and soil moisture [e.g. *Mahowald et al.*, 2006; *Guenther et al.*, 2006]. Foliar VOC emissions are also sensitive to ambient temperature and solar radiation. Emissions could vary by a factor of two or more on time scales of years to decades. An improved understanding of the processes controlling these variations is required for accurate predictions of future natural emissions.

4.6 Harmonization of different inventories

There is no global or common standard for air pollutant emission inventories. Standards and principles for greenhouse gas inventories (e.g., source classification, sources to be included in national totals, definitions of national territories, and pollutant definitions) have been developed by the IPCC [*IPCC*, 1997, 2000, 2006]. The IPCC Guidelines also include ozone precursors (NO_x, NMVOC, and CO) and SO_2. The EMEP inventory has, as far as practical, been adopting the principles of the IPCC Guidelines, but has recently extended the source classification. IPCC is referring to the EMEP/Corinair Guidebook (http://reports.eea.europa.eu/EMEPCORINAIR4/en/page002.html), used for reporting under the LRTAP Convention, as a source of methodology information. The EMEP/Corinair Guidebook provides both simple and more advanced methods for most anthropogenic and natural sources of air pollutants. This Guidebook is currently undergoing a major restructuring and update to be finalized by mid-2008. A manual for air pollutant inventories directed at developing countries to complement the EMEP/Corinair Guidebook has been developed under the Global Atmospheric Pollution Forum (The GAP Forum Air Pollutant Emissions Inventory Manual) (http://www.sei.se/gapforum/). The EDGAR global inventory is also now largely building on the principles of IPCC, especially for the agriculture and waste sectors. In the U.S., the EPA's AP-42 emission factor database (http://www.epa.gov/ttn/chief/ap42/index.html) has been used extensively both in North America and for application to developing countries. Although the EMEP/Corinair Guidebook and U.S. EPA's AP-42 contain similar information, there has not been any serious attempt to harmonize them.

We suggest that further efforts for harmonization of air pollutant inventories use the 2006 IPCC Guidelines, the EMEP/Corinair Guidebook, the GAP Forum manual, and AP-42 as a starting point. Additional work is necessary to define sources specific for key air pollutants, and the extended source list developed by EMEP may need further extension to cover particular sources in developing countries. Furthermore, additional work is needed to define natural sources and to distinguish anthropogenic and natural sources. Methods to estimate emissions may need more development to fully take on board the range of activities and technologies in use in all world regions and the results of recent research. For example BC and OC are not covered by any of the available guidance—though PM_{10} and $PM_{2.5}$ are.

4.7 Recommendations

TF HTAP should make use of the existing emission inventories of EMEP, EDGAR, and other organizations and projects (national governments, GEIA, UNFCCC, etc.). Other research activities can contribute global emission data on topics of special importance to TF HTAP, e.g., shipping and aviation, lightning and other natural sources. TF HTAP should reach out to other organizations and research programs (e.g., TFEIP, GAINS, GAPF, EANET, and CAI-Asia) to facilitate the incorporation of other emission inventories with local knowledge into global emission inventories. Such efforts are especially needed to improve the inventories in regions where emission factors and activity data are poorly known.

Modeling efforts should try to identify those emission estimates (including temporal and spatial resolution) and uncertainties that are most important for understanding intercontinental transport and hemispheric pollution. To evaluate the appropriate attributes of emission estimates, it is necessary to compare the absolute values, ratios, and trends of estimates contained in inventories to values, ratios and trends derived from both ambient observations (surface, in situ, and satellite-based) and atmospheric models, as part of an iterative process. TF HTAP can be an advocate for capacity-building in these areas.

TF HTAP should take into account other efforts to develop future emission projections, including efforts by national governments, TFEIP, UNFCCC (i.e., greenhouse gas emission reporting and national communications), IPCC (i.e., AR5 preparation), GAINS, OECD, QUANTIFY, and others. From these emission projections, efforts should be supported to identify the magnitudes and distributions (spatial, vertical, temporal, and chemical) of expected future emissions changes and to evaluate how these types of changes will change estimates of source-receptor relationships on intercontinental and hemispheric scales.

Improvement of emission inventories and development of projections is of special importance for Asia, because anthropogenic emissions are already larger than those in Europe and North America today and they will continue to increase in the future. To achieve this, TF HTAP should make efforts to improve collaboration with Asian organizations and programs (national governments, EANET, CAI-Asia, etc.).

Finally, we recommend that TF HTAP assist in raising awareness of transboundary and intercontinental air pollution in regions where the concept is less well known and in linking this awareness to the need for improved knowledge of contributing emissions and the importance of building high-quality national and regional emission inventories. TF HTAP can assist in creating crucial links between institutions (including national focal points, regulatory bodies, and research groups) both within countries and across regional and hemispheric scales. These linkages could be an important step in meeting the need of increased capacity for developing good emission inventories throughout the Northern Hemisphere.

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