

# THE 2007 TF HTAP INTERIM ASSESSMENT REPORT

## CHAPTER 4

### Emissions Inventories and Projections for Assessing Hemispheric or Intercontinental Transport

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#### 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<sub>2</sub>, NO<sub>x</sub>, NMVOC, NH<sub>3</sub>, CH<sub>4</sub>, 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 sectors/pollutants 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<sub>2</sub> emissions from power generation in North America and Europe. For other sectors/pollutants and/or regions, 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 such 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 some 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 (CH<sub>4</sub>, NO<sub>x</sub>), agricultural emissions, and biomass burning in remote areas. These may need greater attention from the TF HTAP than they have received 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 relevant scientific communities in these areas could be a valuable function of TF HTAP.

## 4.2 Present-day emission inventories

### 4.2.1 Global inventories and databases

Currently available global emission inventories differ in compounds included, emission sources covered and the spatial and temporal resolution. This is 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/combustion technology and presence of abatement. Some inventories explicitly define control measures and technologies, while in others emission factors are derived from reported/measured emission data (implied factors). Other methods to estimate global emissions are based on inverse modeling to constrain emission estimates with ambient observations and atmospheric model calculations; inverse modeling methods are covered in greater depth in Chapter 6. Table 4.1 provides a summary of relevant global emission inventories that can be used in the HTAP assessment.

**Table 4.1 Overview of global, gridded anthropogenic emission inventories with compounds included that are relevant for HTAP studies**

|                       | Individual studies    | Project-based calculations | Emission databases | Inventory compilations |
|-----------------------|-----------------------|----------------------------|--------------------|------------------------|
| <b>Air pollutants</b> |                       |                            |                    |                        |
| CO                    | ?                     | RETRO, QUANTIFY, POET      | EDGAR, RAINS       | GEIA                   |
| NH <sub>3</sub>       | Bouwman et al. (1997) | -                          | EDGAR(v2)          | GEIA                   |
| NO <sub>x</sub>       | ?                     | RETRO, QUANTIFY, POET,     | EDGAR, RAINS       | GEIA                   |
| NMVOC (total)         | ?                     | RETRO, QUANTIFY, POET      | EDGAR              | GEIA                   |
| NMVOC (speciated)     | ?                     | RETRO, QUANTIFY, POET      | EDGAR(v2)          | GEIA                   |
| SO <sub>2</sub>       | Stern (2005)          | QUANTIFY                   | EDGAR, RAINS       | GEIA, AEROCOM          |
| <b>Aerosols</b>       |                       |                            |                    |                        |
| BC                    | Bond et al. (2004)    | QUANTIFY                   | EDGAR, RAINS       | GEIA, AEROCOM          |

|                 |                    |          |              |         |
|-----------------|--------------------|----------|--------------|---------|
| OC              | Bond et al. (2004) | QUANTIFY | EDGAR, RAINS | AEROCOM |
| <b>Other</b>    |                    |          |              |         |
| CH <sub>4</sub> | -                  | QUANTIFY | -            | -       |

All of the global inventories draw heavily on original 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 of HTAP interest have been studied recently in such special inventories, e.g., NH<sub>3</sub> (Bouwman et al., 1997), BC/OC (Bond et al., 2004), SO<sub>2</sub> (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, vary in level of detail, etc. For some pollutants there are no global studies of this type, e.g., particulate matter. Consequently, there are a number of projects where compilation of specific inventories enhanced with regional work (see next section) and attempts to draw on consistent activity databases lead to the development of large-scale databases for use in global modeling studies. The latter are discussed further in this section.

**EDGAR** 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. 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., 2006; van Aardenne et al., 2005).

The **RAINS** integrated assessment model has been developed by IIASA. Although largely used in regional studies for Europe and Asia, recently it has been extended to estimate global emissions for several compounds, i.e., CH<sub>4</sub>, CO, SO<sub>2</sub>, NO<sub>x</sub> and BC/OC for anthropogenic sources (Cofala et al., submitted). 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. Furthermore, emissions have been allocated to 1° × 1° grid cells based on the EDGAR methodology. Presently, the RAINS model is being transformed into a combined air pollution and climate model (**GAINS**).

To study precursors of ozone and their effects in the troposphere, the **POET** project prepared an emission inventory that included anthropogenic and biomass burning emissions of CO, NO<sub>x</sub>, NMVOC and CH<sub>4</sub> (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 (**GBA reference?**).

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<sub>x</sub>, and NMVOC on a 0.5° × 0.5° grid (Schultz et al., in preparation). Anthropogenic emissions are calculated using the **TEAM** model (**reference?**) that calculates global emissions using an emission factor approach with explicit assumptions about different technologies and abatement measures.

Finally, to quantify the climate impact of global and European transport systems, the **QUANTIFY** project currently develops global emission inventories and scenarios of

anthropogenic emissions of greenhouse gases and air pollutants. In particular, transport emission inventories are calculated and non-transport emissions are taken from the EDGAR 2000 dataset. The results are not yet published.

Although not providing the most recent emissions data, the **GEIA** project has compiled global emission inventories on a  $1^\circ \times 1^\circ$  grid, drawing on other databases (e.g., EDGAR), studies and projects. It includes all pollutants of interest for HTAP. A more recent inventory compilation is the work by Dentener et al. (2006) for the **AEROCOM** project to study aerosol and aerosol precursors. For anthropogenic emissions, data on BC and POM were taken from Bond et al. (2004), while  $\text{SO}_2$  emissions were taken from IIASA (Cofala et al., submitted). For emissions from international shipping and to distribute emissions on a  $1^\circ \times 1^\circ$  grid, data from EDGAR (Olivier et al., 2006) were applied. Biomass burning emissions have been taken from the GFED database (van der Werf et al., 2003).

An illustration of the relative importance of different sectors to global emissions of air pollutants and aerosols is presented in Table 4.2. The data are taken from EDGAR FT2000 (Olivier et al., 2006), except the data on BC and OC, which are based on EDGAR year 2000 activity data and Bond et al. (2004) emission factors. For  $\text{NH}_3$  the emissions are based on EDGARv2 data (1990) scaled with trends from Bouwman et al. (1997). The importance of specific sectors will vary between regions and countries.

**Table 4.2 Overview of the importance of different sectors to global emissions (Unit: % of total emissions).**

|                       | Large stationary combustion |         | Small stationary combustion |         | Transport |          | Industrial processes | Agriculture | Waste | Biomass Burning |
|-----------------------|-----------------------------|---------|-----------------------------|---------|-----------|----------|----------------------|-------------|-------|-----------------|
|                       | Fossil fuel                 | Biofuel | Fossil fuel                 | Biofuel | Road      | Non-road |                      |             |       |                 |
| <b>Air Pollutants</b> |                             |         |                             |         |           |          |                      |             |       |                 |
| CO                    | 2                           | 1       | 3                           | 24      | 19        | 1        | 4                    | 0           | 0     | 46              |
| $\text{NH}_3$         | 0                           | 0       | 0                           | 0       | 0         | 0        | 1                    | 82          | 6     | 8               |
| NOx                   | 28                          | 1       | 2                           | 5       | 22        | 13       | 5                    | 0           | 0     | 23              |
| NMVOc                 | 23                          | 2       | 4                           | 16      | 20        | 3        | 16                   | 0           | 2     | 17              |
| $\text{SO}_2$         | 62                          | 0       | 6                           | 2       | 2         | 6        | 19                   | 0           | 0     | 2               |
| <b>Aerosols</b>       |                             |         |                             |         |           |          |                      |             |       |                 |
| BC                    | 3                           | 2       | 15                          | 22      | 14        | 5        | 0                    | 0           | 0     | 38              |
| OC                    | 1                           | 3       | 2                           | 21      | 4         | 0        | 0                    | 0           | 0     | 69              |
| <b>Other</b>          |                             |         |                             |         |           |          |                      |             |       |                 |
| $\text{CH}_4$         | 30                          | 0       | 1                           | 4       | 0         | 0        | 0                    | 40          | 18    | 6               |

#### 4.2.2 Regional 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. While these assessments cannot be described here in any detail, some important ones need to be mentioned. It is also worthwhile to mention that 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, agriculture, etc., in Asia more pollutant-oriented work has been published. In Europe and the U.S., special inventories and measurement work have been used to develop emission inventory guidelines (**CORINAIR, AP-42 correct references**) that became part of legislation 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/OC) for past, present and future years and is distributed both by source and on a 50 km × 50 km grid. The origin of the data is official national submissions from Parties to the CLRTAP. Where such submissions are missing or are incomplete, the inventory is gap filled by EMEP. Recently a three-stage review process has been established. The latest data and results of the latest review are available from Vestreng et al., 2006.

The **RAINS** model has been independently developed for Europe (Amann et al., 2004; Kupiainen and Klimont, 2006) and Asia (Cofala et al., 2004; Klimont et al., 2001) and includes detailed sectoral emission assessments for countries (Europe) and countries/states/provinces (Asia). RAINS calculates emissions for all HTAP pollutants for the period 1990-2030, based on an emission factor approach, and its databases for Europe have been subject to 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/>).

The European Pollutant Emission Register (**EPER**) includes emissions to air (and water) of approximately 9,200 industrial facilities in the 15 Member States of the EU, as well as Norway and Hungary, mostly for the year 2001, and approximately 12,000 facilities in the 25 Member States of the EU and Norway for the year 2004. EPER will be developed to include more facilities in the future. (**link or reference?**)

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 XXX inventory (XXX)**. For some countries in Asia, there are excellent 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 other parts 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). What emission estimates there are 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 future years.

Within Europe and North America, several countries have established emission inventory programs, primarily as a response to reporting requirements in international and national legislation. Where such programs have become well-established institutions, they provide regular, consistent and transparent emission inventories that are often also of great value to compilers of larger scale emission databases, although each country will have its own specific elements that are developed far better than other, less relevant source sectors. Examples of such inventories are the U.S. (ref), the United Kingdom (ref), and Norway (ref). Comparable institutions do not exist yet in most of Asia and, even if they do, they have little experience for estimating more than just one or two of the major pollutants and very often do not include all source types nor cover the whole of their territory. In such countries, special research inventories and international databases are often the primary sources of information, leading possibly to inappropriate or incomplete representation of some national specificity.

A slightly different case is Russia, where official emission reporting has been institutionalized a long time ago, but the system has been relying on mostly outdated information about emission factors and often not covering non-point sources that are poorly or not at all regulated. The same situation now exists in several of the former Soviet Republics. We argue that a more complete and consistent picture might be developed when using local inputs for the international projects where internal consistency and more complete coverage can be assured.

*[We can try to put together a table similar to Table 4.1 where on the left side we can have pollutants, columns could be regions (North America, Europe, Russia, Asia) and years could be in brackets next to the inventory/model name. ANYONE WANT TO MAKE A START ON THIS?]*

### **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. We will here briefly introduce methods to obtain such uncertainty estimates and some key conclusions. 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, and here will only provide key conclusions from comparisons of inventories with observations and modeling.

#### **4.3.1 Quantification of uncertainties**

Statistical approaches to estimate uncertainties in emission inventory levels and trends have been developed by the IPCC (2006), and these methods can be applied also to air pollutant inventories. Two approaches are given: Approach 1 is simple error propagation and Approach 2 uses 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 standard for expressing uncertainty estimates is two standard deviations as a percentage of the mean.

#### **4.3.2 Intersection of inventories with observations and modeling**

Since about the year 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 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) tried to reconcile 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 Stavrou (2005) on CO and NO<sub>x</sub> and Merink et al. (2006) on CH<sub>4</sub>. Similarly, there are an ever-growing number of satellite-based studies of emission trends, of which Richter et al. (2005) on China's NO<sub>x</sub> emission trends was the seminal work. Again, Chapter 6 expands on satellite-based observations. From the perspective of emission inventories, it is clear that there are potentially large benefits and opportunities to be gained by working together with the atmospheric science community to identify deficiencies in inventory estimates.

#### **4.3.3 Important/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 (for example Western Europe and North America) compile inventories with lower uncertainties than most other regions. Present inventories are generally less uncertain than time-series due to gradually improved scientific knowledge and better statistical data. However, for many of the former Soviet Union states large changes in their statistical system still cause problems.

Differences in uncertainties between sources happen because (a) activity statistics are missing or weak; (b) emission factors are better studied and technologies better known for some sources; and (c) 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 transport and large industrial stationary sources. On the other hand, for countries and regions where the information on control technologies and their efficiency is inadequate, emissions from transport and industry may be as uncertain as the other sources. Natural sources and semi-natural (forest fires) are more uncertain than anthropogenic sources.

Pollutant uncertainties differ as a function of the factors discussed above, but also as a function of the experience of compiling an inventory. Normally the uncertainty can be reduced over time. SO<sub>2</sub> inventories have a long history in Europe and North America and can be considered to be relatively certain in those regions. For other world regions, inadequate information about sulphur content of fuel and removal efficiencies may add to the uncertainty. NO<sub>x</sub> inventories can generally be considered to have slightly higher uncertainty than the SO<sub>2</sub> inventory, while NMVOC and CO inventories are more uncertain. Due to the short experience in compiling PM/BC/OC inventories and the lack of data on the distribution of technology types in key regions, these are even more uncertain. BC/OC inventories have uncertainty ranges of -25 % to a factor of two (higher for open burning) (Bond et al., 2004). Reported uncertainty estimates for Europe range as follows SO<sub>2</sub>: around 5% (but up to 25% reported), NO<sub>x</sub>: around 14% (but up to 25% reported), 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<sub>2</sub> and ±37% for NO<sub>x</sub> 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 being known with high uncertainty.

#### **4.4 Projection of future emissions**

##### **4.4.1 Driving forces**

Assuming no catastrophic events, the most important factors determining future emission levels are activity, level of technology development and penetration of abatement. Activity changes are strongly linked to economic growth but 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 is a key factor determining penetration of abatement. Traditionally, national legislation was driving installation of control technology but in some regions international (regional or global) agreements become key drivers. Examples include, the Kyoto Protocol, UNECE CLRTAP Protocols and EU Directives developed to constrain emissions of various species to reach long-term environmental targets specified in strategy documents, e.g., EU Thematic Strategy on Air Pollution (CEC, 2005).

On a national level the economic projections are frequently updated, as well as some key activities, 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., global SRES scenarios and EU energy or agricultural projections. Large-scale projections are of interest for TF HTAP.

#### 4.4.2 Methods

Only a very broad classification of practiced approaches is given below, grouping them into two principal categories:

- Projection of activities generating emissions (energy use, fertilizers, livestock, production of goods), together with production technology development and abatement penetration based on existing and forthcoming legislation (a variant could be that production technology including abatement evolves in time towards better technology autonomously and described by a functional relationship, see (Streets et al., 2004))
- Projections of proxies like population, economic growth to grow/change emissions over time assuming little or no change in unit emissions; a possible enhancement would be to use elasticity against emissions to account for improvements in production technology or possible increases in penetration of abatement, but this requires historical data to develop such elasticities.

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

#### 4.4.3 Future emission inventories

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

The **IPCC SRES** are well-known and reflect a large, global, long-term effort to prepare, and so cannot be updated very often (the last scenarios were developed in the mid a990's); and although they assume improvements in production technology, they miss changes in the future penetration of abatement (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. (submitted) developed global projections for air pollutants (excluding NMVOC, NH<sub>3</sub>, and PM) and methane out to 2030. The spatial resolution varies by continent, i.e., countries and provinces for the Northern Hemisphere, SRES regions for the rest of the World. A longer-term projection (up to 2100) for BC/OC but taking into account also CO<sub>2</sub> abatement options and policies was prepared by Rao et al. (2005). The activity data draws on SRES scenarios and regional aggregation is also consistent with SRES. As part of its Clean Air Interstate Rule (CAIR), the U.S. EPA has developed near-term emission forecasts of SO<sub>2</sub> and NO<sub>x</sub> (<http://www.epa.gov/cair/index.html>).

The RAINS model for Europe has been used in several policy processes, most recently in the EU NEC review where mid-term projections of activities and emissions of several compounds were developed in consultation with national experts (Amann et al., 2006). These data cover air pollutants (including PM) and GHG extending until 2030. The EMEP database contains official projections for several European countries. These are submissions of countries and they often lack background data that would allow for reconstruction and so are not fully transparent. The data contain air pollutants and extend until 2010.

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 results of these projections for air pollutants are documented in (Klimont et al., 2001). It has been partly updated (reflecting changes in legislation) in new work on the global inventory (Cofala et al., submitted), where new projections for Russia have also been developed. The database includes air pollutants (no PM) and extends until 2030. At global scale and for many regions in the Northern Hemisphere, projections of size-resolved and species-resolved PM have not been developed.

#### **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), wetlands methane (Fung et al., 1991), and wildfires (van der Werf et al., 2003). The resolutions of these models range from hourly and  $1 \text{ km} \times 1 \text{ km}$  for plant foliage VOC to monthly and  $1^\circ \times 1^\circ$  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  $\text{NH}_3$  from wildfires are much higher than those associated with isoprene from foliage and  $\text{CO}_2$  from fires.

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). For example, the driving variables required to estimate foliar VOC emissions include temperature, solar radiation, Leaf Area Index, and vegetation type. Uncertainties in these inputs result in isoprene emission uncertainties of  $\sim 25\%$  for global annual emissions and more than a factor of three for specific location and season. 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 so are not independent estimates. Global satellite observations are beginning to provide a valuable tool for assessing emissions of foliar isoprene (Shim et al., 2005), wildfires (Pfister et al., 2005),

wetlands ([Nature paper](#)), 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, 1996; IPCC 2006). The IPCC Guidelines also include ozone precursors (NO<sub>x</sub>, NMVOC, and CO) and SO<sub>2</sub>. 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, 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 GAP Forum (The Global Atmospheric Pollution Forum Air Pollutant Emissions Inventory Manual). 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 has been used extensively both in North America and for application to developing countries. Although the EMEP/Corinair Guidebook and U.S. EPA 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<sub>10</sub> and PM<sub>2.5</sub> are.

#### **4.7 Recommendations**

The TF HTAP should make use of the existing emission inventories of the CLRTAP and other organizations/projects (national governments, GEIA, EDGAR, UNFCCC, EMEP, etc.) in the assessment of intercontinental transport of air pollution. Other research activities can contribute global emission data on topics of special importance to HTAP, e.g., shipping and aviation emissions or the emissions from lightning and other natural sources. THE TF HTAP should reach out to other organizations and research programs (e.g., TFEIP, GAINS, GAPF, EANET, 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 help identify those emission estimates and uncertainties that are most important for understanding intercontinental transport and hemispheric pollution and the temporal and spatial resolution of emission estimates needed to understand intercontinental transport. To evaluate the appropriate attributes of emission estimates, it is necessary to compare the absolute values, ratios, and trends of emission estimates contained in inventories to emission estimates, ratios, and trends derived from both ambient observations (surface, in situ, and satellite-based) and atmospheric models in an iterative process. The TF HTAP can be an advocate for capacity-building in these areas.

The TF HTAP should take into account other efforts to develop future emission projections, including efforts by national governments, TFEIP, UNFCCC (i.e., 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.

Finally, we recommend that the 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 robust national and regional emission inventories. The 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.

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