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HTAP_v2: a mosaic of regional and global emission gridmaps for 2008 and 2010 to study hemispheric transport of air pollution

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Abstract

The mandate of the Task Force Hemispheric Transport of Air Pollution (HTAP) under the Convention on Long-Range Transboundary Air Pollution (CLRTAP) is to improve the scientific understanding of the intercontinental air pollution transport, to quantify impacts on human health, vegetation and climate, to identify emission mitigation options across the regions of the Northern Hemisphere, and to guide future policies on these aspects.

The harmonization and improvement of regional emission inventories is imperative to obtain consolidated estimates on the formation of global-scale air pollution. An emissions dataset has been constructed using regional emission gridmaps (annual and monthly) for SO_2, NO_x, CO, NMVOC, NH_3, PM_{10}, $PM_{2.5}$, BC and OC for the years 2008 and 2010, with the purpose of providing consistent information to global and regional scale modelling efforts.

This compilation of different regional gridded inventories, including the Environmental Protection Agency (EPA)'s for USA, EPA and Environment Canada's for Canada, the European Monitoring and Evaluation Programme (EMEP) and Netherlands Organisation for Applied Scientific Research (TNO)'s for Europe, and the Model Intercomparison Study in Asia (MICS-Asia)'s for China, India and other Asian countries, was gap-filled with the emission gridmaps of the Emissions Database for Global Atmospheric Research (EDGARv4.3) for the rest of the world (mainly South-America, Africa, Russia and Oceania). Emissions from seven main categories of human activities (power, industry, residential, agriculture, ground transport, aviation and shipping) were estimated and spatially distributed on a common grid of $0.1^\circ \times 0.1^\circ$ longitude–latitude, to yield monthly, global, sector-specific gridmaps for each substance and year.

The HTAP_v2.2 air pollutant gridmaps are considered to combine latest available regional information within a complete global dataset. The disaggregation by sectors, high spatial and temporal resolution and detailed information on the data sources and references used will provide the user the required transparency. Because HTAP_v2.2

contains primarily official and/or widely used regional emission gridmaps, it can be recommended as a global baseline emission inventory, which is regionally accepted as a reference and from which different scenarios assessing emission reduction policies at a global scale could start.

An analysis of country-specific implied emission factors shows a large difference between industrialised countries and developing countries for all air pollutant emissions from the energy and industry sectors, but not from the residential one. A comparison of the population weighted emissions for all world countries, grouped into four classes of similar income, reveals that the per capita emissions are, with increasing income group of countries, increasing in level but also in variation for all air pollutants but not for aerosols.

1 Introduction

Intercontinental transport of air pollution occurs on timescales of days to weeks and, depending on the specific type of pollutant, may contribute substantially to local scale pollution episodes (HTAP, 2010). Common international understanding of global air pollution and its influence on human health, vegetation and climate, is imperative for providing a basis for future international policies and is a prime objective for the Task Force Hemispheric Transport of Air Pollution (TF HTAP)[1]. While nowadays many countries and regions report their air pollutant emissions, these estimates may not be readily accessible, or may be difficult to interpret without additional information, and their quality may differ widely, having various degrees of detail and being presented in different formats.

The UN Framework Convention on Climate Change (UNFCCC) requires official inventory reporting that complies with the TACCC principles of quality aiming at Trans-

[1] More info on www.htap.org.

parency, Accuracy, Consistency, Comparability and Completeness[2], reviewed by UNFCCC roster experts and made available at their website (UNFCCC, 2013). Under the CLRTAP the parties need to report emissions to the EMEP Centre for Emission Inventories and Projections (CEIP), which also reviews data on completeness and consistency. Responsibility of providing emission inventories to several international bodies is often distributed within a particular country and so an inventory for, for example, methane can be provided by different organisations and although they represent the same region they might be different, in fact often are, leading to confusion we need to work with (Janssens-Maenhout et al., 2012).

Currently available emission inventories differ in spatial and temporal resolution (“consistency”), in coverage of geographical area, time period and list of compounds (“completeness”) and in the sector-specific details of the source calculation (“transparency”). Moreover the official inventories submitted by countries have at least one year time lag, are updated with different frequency and with or without review of the historical time series. The work of Lamarque et al. (2010) provides a unique example of a comprehensive “composite” historical emissions dataset spanning from 1850 to 2000, mainly based on scientific estimates. The dataset also provided harmonized base-year (2000) emissions that were used as a starting point for the development of the so-called RCP (Representative Concentration Pathways) emission scenarios (e.g. Moss et al., 2010; van Vuuren et al., 2011). For other years and specific model domains covering multiple regions, atmospheric modellers often compile their own emission inputs drawing upon different pieces of the available inventories. These compilations involve sometimes arbitrary choices, and are often not clearly described or evaluated. For example, the atmospheric modelling groups, which contributed to the HTAP multi-model experiments described in HTAP (2010), used their own best estimates for emissions for the year 2001, obtaining in some cases comparable global emissions (e.g. for NO_x and SO_2), and sometimes getting larger differences (e.g. for NMVOC emissions).

[2]Timeliness is recently also considered.

Moreover, Streets et al. (2010) evaluated the consistency of the emissions used in the various models and nationally reported emissions. For a follow-up study in HTAP Phase 2, it was recommended to provide a harmonised emissions dataset for the years 2008 and 2010 in line with the following 4 major objectives:

1. To facilitate development mitigation policies by making use of well documented national inventories;

2. To identify missing (anthropogenic) sources and gap-fill them with scientific inventories for a more complete picture at global scale;

3. To provide a reference dataset for further emission compilation activities (benchmarking or scenario exercises);

4. To provide a single entry point for consistent global and regional modelling activities focusing on the contribution of long-range (intercontinental) air pollution to regional air quality issues.

A harmonized global, gridded, air pollution emission dataset has been compiled with officially reported, gridded inventories at the national scale, to the extent possible and complemented with science-based inventories for regions and sectors where nationally reported data were not available.

Whereas for a preceding dataset[3] of EDGAR-HTAP_v1 the nationally reported emissions, combined with regional scientific inventories and gapfilled with the global set originating from EDGARv4.2 were all gridded with geospatial data from EDGAR

[3]EDGAR-HTAP_v1 completed in October 2010 comprises sector-specific annual gridmaps for the six years from 2000 to 2005 and covers air pollutants (CH_4, CO, NH_3, NMVOC, SO_2 and NO_x) and particulate matter with its carbonaceous speciation (PM_{10}, $PM_{2.5}$, BC and OC). The annual gridmaps of $0.1^\circ \times 0.1^\circ$ resolution are made available via http://edgar.jrc.ec.europa.eu/national_reported_data/htap.php and the CIERA and ECCAD servers. Documentation is available in the HTAP_v1 EUR25229EN report of Janssens-Maenhout et al. (2012) (http://edgar.jrc.ec.europa.eu/htap/EDGAR-HTAP_v1_final_jan2012.pdf).

(Janssens-Maenhout et al., 2012), this time we used regional gridded emissions, which are officially accepted and complemented with EDGARv4.3 gridmaps (Janssens-Maenhout et al., 2013) for countries or sectors without reported data.

The resulting dataset, named HTAP_v2.2, is a compilation of annual and monthly gridmaps of anthropogenic air pollution emissions (with a 0.1° × 0.1° grid resolution). It contains region-specific information on human activity (concerning intensity and geospatial distribution) and on fuel-, technology- and process-dependent emission factors and end-of-pipe abatement, but it is not as consistent as a globally consistent emission inventory using international statistics and global geospatial distributions. With the perspective of being used in chemical transport models, this inventory includes the atmospheric gaseous pollutants (SO_2, NO_x, CO, NMVOC[4], NH_3) and particulate matter with carbonaceous speciation (PM_{10}, $PM_{2.5}$, BC and OC)[5].

This paper provides a detailed description of the datasets and of the methodology used to compute the 0.1° × 0.1° gridmaps for 2008 and 2010, which are delivered via the EDGAR JRC website (see Sect. 4). Section 2 defines the considered emitting sectors and presents the original data sources: (a) the officially accepted regional/national gridded emission inventories, which were mainly provided by national and international institutions, and (b) EDGAR_v4.3 for gap-filling the remaining regions and/or sectors for some substances. In the HTAP_v2.2 database, gridmaps were merged together

[4]The non-methane volatile organic compounds (NMVOC) of HTAP_v2.2 are defined as the total sum of alkanols, ethane, propane, butanes, pentanes, hexanes and higher, ethene, propene, ethyne, isoprenes, monoterpenes, other alk(adi)enes/alkynes, benzene, methylbenzene, dimethylbenzenes, trimethylbenzenes, other aromatics, esters, ethers, chlorinated hydrocarbons, methanal, other alkanals, alkanones, acids, other aromatics, all expressed in their full weight, not just C.

[5]Whereas PM_{10} is defined as primary emitted aerosols with aerodynamic diameter up to 10 micrometer, $PM_{2.5}$ is a subset with aerodynamic diameter up to 2.5 micrometer, including elemental carbon (BC), organic carbon (OC), SO_4^{2-}, NO_3^{1-}, crustal material, metal and other dust particles. Note that BC and OC are additive to each other but not to $PM_{2.5}$ ($\{BC, OC\} \subset \{PM_{2.5}\}$ and $\{PM_{2.5}\} \subset \{PM_{10}\}$).

with a "collage/mosaic" approach instead of gridding the global emission inventory with one single proxy dataset, as done in for the EDGAR-HTAP_v1 dataset compilation (Janssens-Maenhout et al., 2012). The HTAP_v2.2 inventory aims to obtain more local accuracy on the location of single point sources compared to the previous HTAP_v1, but the downside is that a consistent single location of a specific source of multi-pollutants is no longer ensured, when data originated from different sources, possibly leading to spurious chemical reactions involving non-linear chemistry in the air quality models. Section 3 discusses the resulting gridmaps and addresses the contents of the HTAP_v2.2 compilation methodology, the assumptions, dataflows and consistency of the data used to create the global gridmaps. Whereas HTAP_v2.2 uses more regional bottom-up data (local information on emission factors, on assumed penetration of technology and end-of-pipe control measures in the facilities), the higher spatial accuracy is sometimes overshadowed by artefacts at borders- at least when graphically displaying the data. This is followed with an evaluation of the HTAP_v2.2 by comparing per capita emissions, emissions per unit of GDP and implied emission factors for the different countries. The concluding Sect. 4 summarises the purposes, content and access to this dataset that is currently in use by the HTAP modellers community.

2 Methods

2.1 Defining the sector-specific breakdown

For the development of HTAP_v2.2, a detailed cross-walk table of the US EPA, EDGAR and EMEP (sub)sector-specific activities has been setup, using all human activities defined in detail by IPCC (1996) and applied for the reporting under the UNFCCC. The US EPA and the contributing dataset from Environment Canada, provided the most detailed cross-walk matrix between the categories used in their national inventory and the full-fledged set of all IPCC categories. However, a higher level of aggregation was needed to find a common basis with the Asian emission inventories, which led to the establishment of the 7 categories: Aircraft, International Shipping, Power Industry, Industry, Ground Transport, Residential and Agriculture (described in Table 1 underneath).

HTAP_v2.2 focusses only on anthropogenic emissions, in a comprehensive way, but excludes large-scale biomass burning (forest fires, peat fires and their decay) and agricultural waste or field burning. We refer to inventories such as GFED3 (van der Werf, 2010) for the forest, grassland and Savannah fires (IPCC categories 5A + C + 4E) and to the 1° × 1° gridmaps of Yevich et Logan (2003) or the 0.1° × 0.1° EDGARv4.2 gridmaps (EC-JRC/PBL, 2011) for the agricultural waste burning (4F). Moreover, only NH_3 emissions from the agricultural sector were taken up in the htap_8_Agriculture sector of HTAP_v2.2 inventory, so that the occasionally reported NO_x from agricultural waste burning or from biological N-fixation and crop residues (which is typically considered under S10 for Europe) are excluded.

2.2 Gridded input datasets for HTAP_v2.2

As explained earlier, the goal of the HTAP_v2.2 inventory is to provide consistent and highly resolved information (see Fig. 1a) to global and regional modelling. It is important to realize that in the HTAP modelling exercise both global and regional models are participating. The HTAP global modelling is coordinated with the regional modelling exercise of Air Quality Model Evaluation International Initiative AQMEII (Galmarini et al., 2012, 2015) that manages regional scale activities for Europe and North America, and the regional modelling exercise of the Model Intercomparison study for Asia MICS-Asia (Carmichael et al., 2008) that manages the regional modeling over Asia. Hence, the regional inventories used for HTAP_v2.2 are constructed and used in accordance with these regional activities.

2.2.1 USA and Canada: EPA and Environment Canada gridmaps and EPA temporal profiles

EPA (2013) provides the 2008 and 2010 areal and point source emissions for the complete North American domain at 0.1° × 0.1° resolution, covering USA with a grid ranging from 180–63° W in longitude and 75–15° N in latitude and covering Canada with a grid from 142–47.8° W in longitude and 85–41° N in latitude. Mexico is not covered by these latitudes and it is gapfilled with EDGARv4.3 data (see Sect. 2.2.4). For the northern latitudes above 45° N, Environment Canada provided the 2008 basis and an update of the point sources for 2010, from which US EPA prepared the full set of detailed gridmaps also for 2010. The temporal profiles of US EPA were applied for USA and Canada with identical monthly distributions per sector for 2008 and 2010. More details about the US inventory are given by Pouliot et al. (2014, 2015).

2.2.2 Europe: TNO gridmaps and EMEP temporal trends

Countries that are parties to the CLRTAP (www.unece.org/env/lrtap/lrtap_h1.html) need to report anthropogenic emissions of air pollutants and particulate matter, but neither BC nor OC. These reported/official inventories are reported on the national level to EMEP-CEIP[6] which provides the annual emission inventory data for CO, NH_3, NMVOC, NO_x, SO_x, PM_{10} and $PM_{2.5}$ (not BC and not OC). However, the currently used EMEP grid uses a polar-stereographic projection with about 50 km × 50 km grid cells centered over the European region and converting to a Mercator projection implied a loss of spatial accuracy. These reported data are incomplete according to the CEIP annual report of Mareckova et al. (2013) and for evaluation with the EMEP unified model further gapfilling is needed, resulting in a semi-official emission dataset. To overcome the problems of inconsistent emissions time series and fulfil the need for a higher spatial resolution to support AQ modelling in Europe in the European FP7 project Monitoring

[6]More info on www.ceip.at.

Atmospheric Composition and Climate (MACC), TNO established a scientifically complete and widely accepted dataset, which is fully documented by Kuenen et al. (2014). This so-called TNO-MACC-II inventory of Kuenen et al. (2014) covers the same European domain with areal and point source emission gridmaps at 1/8° × 1/16° resolution for SO_2, NO_x, CO, NMVOC, NH_3, PM_{10}, $PM_{2.5}$ with point sources allocated to their exact location. The grid-domain ranges from 30° W–60° E in longitude and 72–30° N in latitude. The geographical area covered all EU-28 countries, Switzerland, Norway, Iceland and Liechtenstein, Albania, Bosnia-Herzegovina, Serbia, Macedonia, 6 Newly Independent States (Armenia, Azerbeijan, Belarus, Georgia, Moldova, Ukraine) and Turkey. Countries with partial coverage (Russia, Turkmenistan, Kazakhstan and Uzbekistan) were not used in the HTAP_v2 inventory because of inconsistencies with other datasets (see Sect. 2.2.4). Sector-specific data (given by SNAP-code, see Table 1) are used for all countries with complete coverage of their territory and for each substance the contribution from each sector is compared to EMEP and EDGARv4.3 estimates. Standard re-sampling is applied to obtain gridmaps at the common resolution of 0.1° × 0.1°. Point-source, ground-level airport emissions in the transport sector (under SNAP 8) were taken out, in order to avoid a double counting with the aviation sector (HTAP_1), for which the same geospatial dataset taken from EDGAR_v4.3 was used globally.

For NH_3, the reporting of emissions from the energy, industry and residential sectors was apparently negligible for some countries[7] compared to the agricultural emissions and was therefore not gapfilled by EMEP and/or TNO.

BC and OC emission data are not available as emission gridmaps within the MACC-II dataset, but the PM gridmaps are accompanied by a recommendation on the PM com-

[7]No NH_3 emissions are reported in the energy sector: for the countries Albania, Bosnia-Herzegovina, Cyprus, Estonia, Greece, Ireland, Iceland, Luxembourg, Latvia, FRY Macedonia, Malta, Norway, Poland, Romania, Slovakia, and Slovenia; in the industry sector for the countries Albania, Bosnia-Herzegovina, Greece, Ireland, Iceland, and FRY Macedonia; and in the residential sector for the countries Greece, Iceland and Slovenia.

position describing the carbonaceous profiles per SNAP code and country. This so-called PM split table (per SNAP code and country) of TNO (TNO, 2009) is used to derive the BC and OC from PM_{10} and $PM_{2.5}$ emission gridmaps (see Kuenen et al. (2014) for details).

Finally, to derive the monthly gridmaps we used the country-specific and sector-specific data monthly profiles per substance for the EMEP model (M. Schulz, personal communication, 2013 and A. Nyiri personal communication, 2013).

2.2.3 Asia: monthly gridmaps from MIX

For Asia, a different challenge is faced, because no countries except Japan are legally required to yearly report detailed emission inventories under the LRTAP, UNFCCC or similar conventions. However, in Asia many scientific efforts aimed at establishing a detailed emission inventory, accepted by the different regions, using official or semi-official statistics collected at county level (by provinces for China). Under the Model Intercomparison Study for Asia Phase III (MICS-Asia III), a mosaic Asian anthropogenic emission inventory was developed for 2008 and 2010 (Li et al., 2015). The mosaic inventory, named MIX, incorporated several local emission inventories including the Multi-resolution Emission Inventory for China (MEIC), NH_3 emission inventory from Peking University (Huang et al., 2012), Korean emissions from the Clean Air Policy Support System (CAPSS) (Lee et al., 2011), Indian emissions from the Argonne National Laboratory (Lu et al., 2011), and fill the gap where local emission data are not available using REAS2.1[8] developed by Kurokawa et al. (2013).

MEIC is developed by Tsinghua University under an open-access model framework that provides model-ready emission data over China to support chemical transport

[8]The REAS2.1 inventory for Japan includes the data developed by Ministry of the Environment of Japan (MOEJ, 2009) for NMVOC evaporative emissions from stationary sources, the database developed by the Ocean Policy Research Foundation (OPRF, 2012) for the maritime sector, and the Japan Auto-Oil Program Emission Inventory-Data Base (JEI-DB) developed by Japan Petroleum Energy Center (JPEC, 2012a–c) for other sources.

models and climate models at different spatial resolution and time scale. In the MIX inventory, the MEIC v.1.0 data was used which contains the anthropogenic emissions of China for SO_2, NO_x, CO, NMVOC, NH_3, CO_2, $PM_{2.5}$, PM_{coarse}, BC, and OC for the years 2008 and 2010 with monthly temporal variation at 0.25° × 0.25°. For India, MIX used the Indian emission inventory provided by ANL for SO_2, BC, and OC and REAS2.1 for other species. With the input from different regions, the MIX inventory provided harmonized emission data at 0.25° × 0.25° grid resolution with monthly variation for both 2008 and 2010. The detailed mosaic process of the MIX inventory is documented in Li et al. (2015). Reported emissions from countries which are only partly covered by the MIX, like Russia, Turkmenistan, Uzbekistan and Kazakhstan were not taken up in the HTAP inventory and instead gap-filling by EDGARv4.3 was used (see Sect. 2.2.4).

As such, a broad area, ranging from 89.875° N to 20.125° S in latitude and from 40.125° E to 179.875° E in longitude was after a raster-resample procedure covered by 0.1° × 0.1° emission gridmaps. Monthly gridmap results (without distinction between point and areal sources and without temporal profiles) are given per sector (energy, industry, residential, transport, and agriculture only for NH_3).

2.2.4 Rest of the world covered by EDGARv4.3

The Emission Database for Global Atmospheric Research (EDGAR) of EC-JRC/PBL (2011) provides historical (1970–2008) global anthropogenic emissions of greenhouse gases[9] CO_2, CH_4, N_2O, HFCs, PFCs and SF_6, of precursor gases, such as CO, NO_x, NMVOC and SO_2 and of aerosols, including PM_{10}, $PM_{2.5}$, BC and OC per source category at country level on 0.1° × 0.1° gridmaps. Emissions are calculated by taking into account human activity data of IEA (2013) for fuel consumption and of FAO (2012) for agriculture, different technologies with installed abatement measures, uncontrolled emission factors (IPCC, 2006) and emission reduction effects of control measures

[9] The methodology for the greenhouse gas emission time series applied in EDGARv4.2 is detailed in Olivier and Janssens-Maenhout (2012).

(EMEP/EEA, 2013). Anthropogenic emissions calculations are extended till 2010 for all 246 world countries for the emission source (sub)groups, (i) combustion/conversion in energy industry, manufacturing industry, transport and residential sectors, (ii) industrial processes, (iii) solvents and other product use, (iv) agriculture, (v) large scale biomass burning, (vi) waste and (vii) miscellaneous sources. A detailed overview of the EDGAR emissions database and how it can be used for gapfilling can be found in Balsama et al. (2014).

The EDGAR emission data are spatially distributed using an extensive set of global proxy data, which are representative for major source sectors and documented in the EDGAR gridding manual of Janssens-Maenhout et al. (2013). For HTAP_v2.2, the EDGARv4.3 database provides yearly emission gridmaps with a resolution of 0.1°×0.1° for the "rest of the world" countries of Table S1.2 of Annex I in the Supplement for all pollutants (SO_2, NO_x, CO, NMVOC, NH_3, PM_{10}, $PM_{2.5}$, OC, BC) and HTAP sectors for the years 2008 and 2010. The htap_2 Ships data are provided for the entire world, while the htap_1 Aviation data are provided for the entire world for the international part and for the world excluding USA and Canada for the domestic aviation. Monthly emissions gridmaps are generated from the annual emission data per HTAP sector using EDGAR monthly factors defined for the three different zones: Northern Hemisphere, Equatorial region and Southern Hemisphere (Table S1.2).

The countries with partial geo-spatial coverage under the MACC-II and MIX inventories (see Sects. 2.2.2 and 2.2.3) are completely replaced with EDGARv4.3 data to avoid inconsistencies and artefacts at the border between two datasets within one country (such as Russia, Kazakhstan, Turkmenistan and Uzbekistan).

3 Results

Monthly global gridmaps were produced for 2008 and 2010 and are available per htap sector and substance at http://edgar.jrc.ec.europa.eu/htap_v2/index.php?SECURE=123. We describe major characteristics of the gridmaps in Sect. 3.1. We focus on

2010 but the observations remain valid for 2008 (in the same period of recession). A summary graph of the emission totals and their sector-specific composition is given in Fig. 1b. In Sects. 3.2 and 3.3 we put the country totals (given bottom-up except for the MICS-Asia regions, where we derived the totals from the gridmaps) in perspective with a comparative analysis of the emissions per capita and emissions per GDP for low, lower middle, upper middle and high income country groups. To estimate how polluting the activities are in the different regions, Sect. 3.4 addresses the implied emission factors. Finally, we address the difference in emissions 2008 to 2010 in Sect. 3.5 and we conclude with a qualitative assessment of the uncertainty of the gridmaps in 3.6.

3.1 Spatial distribution of global emissions per sector

An overview on the region-specific totals and the composition per region and sector is given in the 9 maps of Fig. 2a–i for the different substances for the year 2010. The sector-specific country-totals are given in Table S1.1 and the totals for each of the 16 HTAP source region, as defined for the source-receptor calculations of the HTAP modelling community and described in Table S2.1 are given in Table S2.2 of Annex II in the Supplement.

Developing countries contribute from 70 % to more than 90 % to the current global anthropogenic pollutant emissions, depending on the considered compound and Asian countries are the major emitters, contributing from 40 to 70 %. Among these countries, China and India represent two densely populated regions, producing together more than two thirds of the total Asian emissions. On the contrary, developed regions (like North America and Europe) produce much lower emissions, representing overall from 30 % down to 10 % of the total annual global anthropogenic emissions. Since the rest of the world group of countries includes a variety of regions, differing in population, human activities, types of industries, etc., it is crucial to disaggregate it into its components. In particular for $PM_{2.5}$ and somewhat less for NO_x, Asia strongly contributes to the global emissions compared to the contribution of North America and Europe.

Generally, higher emissions are observed for populated areas and coastal regions, but specific features can be highlighted depending on the pollutant and activity for specific countries per substance. The differences of the Fig. 2a–i in the sector-specific composition (pie charts) of the emission sources for world regions (represented by the color scale) vary strongly between compounds. Some of the factors include:

- For SO_2 the emissions will depend on the importance of coal used in the industry and residential sectors and the degree of flue gas desulphurization. In some regions non-ferrous metals industry will be of great importance.
- For NO_x emissions industrial combustion and transport are key and with increasing level of activity the application of end-of-pipe controls, including catalytic reduction of flue gases, is playing an ever increasing role.
- CO and NMVOC emissions are dominated by incomplete combustion (cooking and heating stoves) and transport, especially in absence of advanced controls. For NMVOC additionally evaporative losses from solvent use and oil industry are of high relevance.
- Finally for PM, incomplete combustion (stoves) and in developing countries poor efficiency of filters installed on industrial boilers can be a source of large emissions while more recently transport emissions from diesel engines became of concern.

3.1.1 SO_2

The Asian region keeps suffering from a relative large contribution of SO_2 from (coal fired) power plants and manufacturing industry. Most of the SO_2 emitted in North America and Europe comes from coal power plants. However, in Europe Fig. 2a shows that SO_2 is also emitted from the residential and waste disposal sector. Residential (heating and cooking) and waste disposal sources are particularly relevant in Africa. High annual SO_2 emissions are also observed for India and correspond to high contributions from the industrial combustion, using also coking and bituminous coal in the power and iron and steel industry according to IEA (2013). Finally, international shipping contributes ~ 10 % to the global SO_2 emissions. SO_2 gridmaps clearly show the ship emission tracks connecting Asia and Europe with Africa and America.

3.1.2 NO_x

Figure 2b shows that the major sources of NO_x are ground transport and power generation and these source contributions show a rather uniform feature for all the considered regions. In Central and South America major emissions are attributed to the transportation sector and just to a minor extent to the energy sector. Those industrialised countries with a large share of natural gas as fuel for heating houses and commercial centres (such as Canada) show relatively high emissions of NO_x. International shipping and, in particular, aviation contribute together more than 10 % of global NO_x emissions.

3.1.3 CO

CO is a product of incomplete combustion, which can therefore be emitted by any fuel combustion (ground transport, industrial processes involving combustion, as well as domestic heating). As presented in Fig. 2c, the power generation sector emits less CO than the residential one because of higher combustion efficiency and higher temperatures compared to domestic burners. In Africa, there are large emissions of CO from the residential sector, mainly due to the use of wood and charcoal for cooking activities. As shown in Fig. 2c, some industrial activities emit CO, like the production of non-metallic minerals and crude steel and iron, which is particularly relevant for India and China, while non-ferrous metal and iron and steel production are dominant in Oceania.

3.1.4 NMVOC

NMVOCs (non-methane volatile organic compounds) are emitted from chemical and manufacturing industries, as well as fuel transformation processes, the production

of primary fuels, the use of solvents and from the residential sector, inclusive waste (Fig. 2d). Important sources of NMVOCs include also evaporative emissions from road transport, specifically gasoline engines and the use of biofuels. Major emission sectors in the USA emitting NMVOCs include oil refineries, oil and gas production, several industrial processes and motor vehicles. Most of the NMVOC emissions in Europe are due to solvent use, road transport, and the use of primary solid biomass in the residential sector. In the Middle East NMVOC sources include oil production and in South-Eastern Asia charcoal production. In China, particular high emissions are also associated with the high use of solvents in paints and in Brazil with the use of biofuels. NMVOC speciation is not provided by the HTAP_v2.2 emission database; however TNO has produced a breakdown into 23 VOC species, which has been used for the RETRO project and the RCP scenarios of IPCC AR5. Recommendations for the NMVOC splits are given on the HTAP wiki site http://iek8wikis.iek.fz-juelich.de/HTAPWiki/WP1.1.

3.1.5 NH_3

NH_3 is mainly emitted by the agricultural sector, including management of manure and agricultural soils (application of nitrogen fertilizers, incl. animal waste), as Fig. 2i shows, while a relatively small amount is emitted by the deployment of catalysts in gasoline cars. Minor contributions are also observed for Asian countries from the residential sector due to dung and vegetal waste burning and coal combustion. For industrialized regions, especially for countries using low sulphur fuel, Mejía-Centeneo et al. (2007) reported that the deployment of catalytic converters in gasoline cars enhanced the NH_3 emissions from this source since mid-2000. This is also observed by the larger NH_3 with increased transport activity and corresponding increased consumption of low sulphur fuels. In the USA gasoline vehicle catalysts represent ca 6 % of total NH_3 emissions, while a lower contribution is found for Europe due to the high deployment of diesel vehicles.

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3.1.6 PM_{10} and $PM_{2.5}$

Particulate matter (PM), both in the fine and coarse fraction, is mainly emitted by biomass and fossil fuel combustion in domestic and industrial activities (Fig. 2e and f). On the contrary, ground transportation contributes ~ 5 % to total PM emissions (excluding non-exhaust road abrasion dust and tyre wear emissions). As depicted in Fig. 1b, developed countries (like USA and EU) represent ~ 10 % of global emissions of PM and its components, while much higher contributions derive from developing countries where less strict legislation is applied in the industrial sector and in road transport. Fig. 2e and 2f show a similar composition of the contributing sectors to PM_{10} and $PM_{2.5}$ globally. PM_{10} and $PM_{2.5}$ gridmaps point out the enhanced PM emissions in Asian countries, due to industrial processes and the residential sector. A decreasing trend from 2008 to 2010 is observed for Brazil due to decreases in emissions from charcoal production. Emissions from charcoal production are also important for India and some African countries, with country-specific shares varying between 1 and 10 %. Western Africa generally emits more PM than the Eastern part because of more industrial activities.

3.1.7 BC and OC

Black carbon (BC), the light-absorbing component of the carbonaceous part of PM, and organic carbon (OC) are emitted from incomplete combustion. Major emission sources are residential cooking and heating (fossil fuel and biomass combustion) and for BC also ground transport (especially diesel engines). Very low emissions originate from the energy sector due to higher process efficiencies and high combustion temperatures. Figure 2g shows that the largest contributing sector for BC in North America, Europe and the Middle East is road transport, mainly from diesel vehicles. Heavy duty and light duty vehicles in these regions, but also diesel passenger cars in Europe and the Middle East, cause this relatively large contribution despite the use of particle filters, which have not yet fully penetrated the fleet. For Asia, Oceania, Africa and Central- and

South-America, the residential sector is the main contributor of BC emissions. China and India emit more BC than Western industrialized countries from the coke ovens and non-metallic mineral industries, as well as from domestic activities involving the combustion of solid biomass and bituminous coal and charcoal production. Most important sources in Russia include primary solid biomass and waste burning in the residential sector and other bituminous coal combustion in the commercial sector and in the cogeneration and heat plants. A different situation is observed for Africa, where in addition to emissions from traffic and oil production, an important role is played by charcoal production and the use of primary solid biomass and charcoal in the residential sector. Nigeria has high flaring emissions from oil and gas production and Kenya and Sudan suffer from large charcoal production activities. For OC (Fig. 2h), all regions except the Middle East show that the largest emission contribution comes from the residential sector (combustion of charcoal and solid biomass). For the Middle East a relatively large contribution from industrial activities (fuel production) is observed.

3.2 Per capita emissions

To compare emissions from worldwide countries characterized by different degrees of development and numbers of inhabitants, per capita emissions were calculated. Country-specific per capita total emissions are given in Table S3.1 of Annex III in the Supplement and an example for three selected countries, USA, Germany and China is given in Table 2 below. Country total population data were obtained from the United Nations Population Division (UNDP, 2013). This approach allocates the emissions from industrial production to a country without taking into account exports. No life cycle assessment of products at the point of consumption is considered here. This production-based approach has limitations as moving heavy industry from industrialized to developing countries under this production-based approach puts a large burden on countries (in particular those with small populations and mining/manufacturing activities for export). For example mining for export is having a growing impact in Oceania (with low population) and industrial production in China for international markets became increasingly important since 2002 when China entered the World Trade Organisation.

For SO_2 the per capita emission in 2010 for EU-28 of 9.1 kg SO_2 cap^{-1} is slightly lower than the reported value of 11.5 kg SO_2 cap^{-1} from EUROSTAT (2014). This is about half the SO_2 per capita for China in 2010 and about one third of the SO_2 per capita for USA. Significant reductions of the Chinese SO_2 per capita emissions started due to the introduction of very strict emission limits followed by ambitious flue gas desulfurization programs in power plants (Lu et al., 2011; Klimont et al., 2013; Wang et al., 2014). China is expected to follow the European example, where the SO_2 per capita decreased from 1995 to 2005 with 65 % of the decrease occurring in Germany and UK according to Ramanathan and Feng (2009).

For NO_x and NMVOC, China is similar to the European per capita levels. North America and Oceania double the level of European and Asian per capita emissions of NO_x and NMVOC for industrial combustion and transport mainly due to their larger fuel consumptions in the industry (Olivier et al., 2013) and road transport (Anderson et al., 2011) sectors, while having similar abatement technologies.

Whereas for NO_x, NMVOC, CO and NH_3, the ranking from lowest to highest per capita emitters in Table 2 is Germany – China – USA, for PM this order is not present. We observe that the PM emissions per capita of Germany are about one fifth of the per capita emissions of the USA, and the per capita $PM_{2.5}$ for China is more than double the per capita $PM_{2.5}$ of the USA. Table S3 indicates that developing countries, in particular those with emerging economies but not yet fully penetrated clean technologies and end-of-pipe measures, have enhanced PM per capita emissions. Russia has high per capita PM emissions for the power generation sector, while Canada shows high values for non-power industry. Both countries show high OC emissions of inland waterway transport using heavy residual fuel oil or diesel.

Figure 3 gives an overview of the per capita emissions for high, upper and lower middle and low income countries, as defined for the WGIII of AR5 of IPCC (2014). The largest variation between the different groups of countries is observed for SO_2

and NO_x, which represent the presence of industry. The median of per capita SO_2 and NO_x emissions are higher for high and upper middle income countries than for low or lower middle income countries. The median of per capita CO and NMVOC is not strongly dependent on the income of the countries, whereas the median of per capita PM (and BC and OC) are definitely lower for high income countries than for low income countries.

3.3 Per GDP emissions

Another indicator of emission intensity of a country is the ratio of emissions and Gross Domestic Product (GDP) in USD, in constant Purchasing Power Parity (PPP), as given in Table S3.2 of Annex III and shown in Fig. 3b. The GDP 2010 data for the different countries were obtained from World Bank (2014) and IMF (2014). This indicator is much more uncertain than the per capita emissions because the GDP is more difficult to cover with the various inhomogeneous economic activities, which are also influenced by time-dependent inflation and currency exchange rates and which are incomplete with the unrecorded unofficial activities. It is recommended to use this indicator only for comparing levels because the correlation between emissions and GDP can be small for countries with a substantially contributing service sector.

For 2010 Fig. 3b shows that EU and USA have similar low emissions per unit of GDP for all substances, except NO_x where EU's emission per unit of GDP is still significantly lower than in USA. China's emissions of SO_2 and NO_x per unit of GDP are at the high end, whereas for NH_3 and the carbonaceous particulate matter China is bypassed by India, which shows even higher emissions per unit of GDP.

3.4 Implied emission factors

Energy-intensity is a widely used indicator to assess the fuel efficiency of manufacturing processes. Analogous to energy-intensity, we analyse in this section air pollution emission-intensity for all world countries. Emission intensity of economic activities for a given region are determined by implied emission factors. The region-specific implied emission factors (EF) present the emissions per unit of activity (per TJ energy consumed for all combustion-related activities, per kg product for industrial processes and solvents or per ha cultivated land for agricultural related activities) and are defined for a substance x with speciation l at time t due to activities AD in activity sector i with technologies j and end-of-pipe measures k, in a country C as:

$$\mathrm{EF}_{C,i}(t,x_l) = \frac{\sum_{j,k}[\mathrm{AD}_{C,i}(t)\cdot \mathrm{TECH}_{C,i,j}(t)\cdot \mathrm{EOP}_{C,i,j,k}(t)\cdot \mathrm{EF}_{C,i,j}(t,x_l)\cdot (1-\mathrm{RED}_{C,i,j,k}(t,x_l))\cdot f_{C,i,j}(x_l)]}{\sum_{j,k}[\mathrm{AD}_{C,i}(t)\cdot \mathrm{TECH}_{C,i,j}(t)\cdot \mathrm{EOP}_{C,i,j,k}(t)]}$$

with TECH representing the technologies, EOP the end-of-pipe measures, EF the emission factors and RED the emission reduction due to end-of-pipe control measures.

Thereto, emissions of sector-specific gridmaps for 2010 have been aggregated to country level and divided with the activity data for that sector in that country from EDGARv4.3, which are for energy-related activities based on IEA (2013) statistics and for agricultural-related activities on FAO (2012) statistics. It should be noted that the aggregation of the country cells, taking into account the relative areal fraction of that country in cross-border cells, needed to be corrected with country-specific reporting, in order to allocate point sources (e.g. power plants) at borders (e.g. waterways) to the responsible country. The implied emission factor results are given for all world countries and for 2010 in the Table S4 of Annex IV in the Supplement.

Figure 4 gives an overview per sector of the range of different implied emission factors for each country with the maximum/minimum, the percentiles and the median. In addition the position in this range of EU27, USA, China and India is indicated to evaluate the level of emission-intensity of the different activities. EU 27 and USA show very similar implied emission factors for the energy and industry sectors, which are much lower than the median for all pollutants. China also shows implied emission factors for energy and industry that are lower than the medians, but still larger than USA and EU 27. India shows much higher implied emission factors for energy and industry, which are for CO, $PM_{2.5}$, BC, and OC above the median. In the case of the residential sector,

the range of variation of the implied emission factors is the smallest for SO_2 and NO_x, but the largest for $PM_{2.5}$ and BC. For the transport sector a relatively large variation is present for CO, with an implied emission factor for China that is above the median. For agriculture it is remarkable that China and India, but also the USA and EU 27, have implied emission factors that are above the median, with China reaching the maximum compared to all other world countries.

Even though only implied emissions factors for country emissions are presented in Fig. 3b, the implied emission factors were also calculated for the international bunker fuel and indicated that the implied emission factors are at the high end of the range for SO_2 (0.98 t SO_2 TJ^{-1} similar to the road transport emission factor of Laos or Panama), NO_x (with 1.65 t NO_x TJ^{-1} similar as for transport in Bangladesh or Myanmar), $PM_{2.5}$ (with 0.17 t $PM_{2.5}$ TJ^{-1} similar as for transport in China), but are relatively low for CO, NMVOC and BC. The high SO_2 implied emission factor might indicate the use of lower quality fuels in sea transportation, especially in international waters.

3.5 Emission changes 2008–2010

The emission change from 2008 to 2010 is given in Table S2.3 of Annex II. For the developed countries in North America and Europe the decline of emissions between 2008 and 2010 for most of the pollutants are driven mostly by continued implementation of emission reduction technologies. In some cases this also leads to increases in sectorial emissions, although insignificant for the total, as is estimated for NH_3 in the energy and transport sectors, due to the use of catalysts.

For the MICS-Asia region, the emissions are mostly increasing except for the energy sector, where the SO_2 and PM emissions are reduced in 2010 due to the wide deployment of flue-gas desulfurization (FGD) and particulate matter filters in the power plants, consistent Wang et al. (2014). For the other developing countries (calculated with the EDGAR data), the SO_2 emissions slightly increase from 2008 to 2010 in the energy sector, possibly due to the impact of increasing coal use (Weng et al., 2012) and even heavy fuel oil (in the Middle East power sector according to IEA (2013) activity data). The PM emissions from the industry of the other developing countries show a decrease from 2008 to 2010, indicating slow penetration of end-of-pipe abatement.

3.6 Qualitative assessment of the uncertainty of emission gridmaps

Even though the HTAP_v2.2 data sources are quite different, and lead to inconsistencies over borders, a bottom-up methodology with activity data and emission factors is applied to calculate emission totals and distribute these on the grid. The propagation of uncertainty is given by the effect of variables' uncertainties (or errors) on the uncertainty, i.e. the variance of the activity data and that of the emission factor. Table 3 provides some insight in the estimation of the uncertainty range, however the approach followed in HTAP v2.2 inhibits an overall consistent uncertainty assessment because it is not a bottom-up inventory.

We can only compare the HTAP v2.2 with the ECLIPSEv5 dataset of Klimont et al. (2015), which is a fully consistently built global bottom-up inventory and serves as base year for the HTAP scenarios. At global level, a relatively good agreement is found with small relative emission differences (ECLIPSEv5 – HTAPv2.2)/HTAPv2.2 for the aggregated sectors in 2010. The relative difference for NO_x and CO is only −4 % respectively +5 %. For SO_2 a larger difference of −8 % reflects the recent important S-reductions for the non-ferrous metal smelters in ECLIPSEv5 (Klimont et al., 2013). For NH_3 a relative difference of +17 % is acceptable because of the larger uncertainty in emission factors driven by lack of information about manure management practices and also by incomplete data on the agricultural activities. For NMVOC a difference of −27 % stems primarily from the assumptions about emissions from solvent use. The information about activity levels is scarce and even less is known about the emission factors for some important sources. Both regional inventory compilers and modellers often make assumptions about per capita or per GDP solvent use NMVOC emissions from particular sectors. Here assumptions employed in the ECLIPSEv5 lead to lower emissions from these activities. As anticipated (and reflected in Table 3) larger differ-

ences of 48 and 29 % are present for $PM_{2.5}$ and BC, respectively. While for $PM_{2.5}$, assumptions about penetration and efficiency of filters in industrial and small-scale residential boilers as well as emission factors and activity data for biomass used in cooking stoves play a key role, for BC assumptions about coal consumption in East Asia are of relevance since ECLIPSEv5 relied on provincial statistics for China which results in higher coal consumption than reported in national statistics and IEA. Additionally, ECLIPSEv5 includes emissions from kerosene wick lamps, especially relevant for South Asia and parts of Africa according to Lam et al. (2012), gas flaring and high emitting vehicles, which together result in about 30 % higher emissions.

In addition, the spatial allocation is subject to other types of errors, with a spatial variance for point sources and a more important systematic error when a spatial proxy is used to distribute the emissions. Geo-spatial consistency is lower in the HTAP_v2.2 database than if the national totals would have been spatially redistributed with one harmonised spatial proxy dataset.

Another type of inconsistency occurs when speciation of a substance is done with gridmaps of different data sources. This was another reason not to use the PM gridmaps of EMEP, as no BC and OC speciation is available from the same EMEP data source. Instead we used the gridmaps of TNO for all PM components (PM_{10} and $PM_{2.5}$) and the TNO speciation file for BC and OC. In addition a check was performed to ensure that the sum of BC and OC emissions in every grid cell is smaller than the $PM_{2.5}$ emission in that grid cell. Thereto a re-allocation of the emissions of some point sources (industrial facilities) was needed within Europe (e.g. Poland) and performed in consultation with TNO.

Another check was to estimate per grid cell the change in emission from 2008 to 2010 and allowed to find missing sources. However, global consistency cannot be guaranteed and a comparison of different countries or of different years cannot be conclusive. In particular point sources are very important input, but their strengths and locations are subject to input errors with larger consequences and cannot be extrapolated in time. (Closure of power plants as large point sources can change the emission distri-

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bution pattern from one year to another.) Feedback from users of the emission dataset has already helped to improve its quality (L. Emmons, personal communications, 2013 and D. Henze, personal communication, 2013) and is further encouraged.

4 Conclusions and recommendations

This paper describes the HTAP global air pollutant baseline emission inventory for 2010, which is also regionally accepted as reference. It assures a consistent input for both regional and global modelling as required by the HTAP modelling exercise. The HTAP_v2.2 emission database makes use of consolidated estimates of official and latest available regional information with air pollutant gridmaps from US EPA and Environ-Canada for North America, EMEP-TNO for Europe, MIX for Asia, and the EDGARv4.3 database for the rest of the world. The mosaic of gridmaps provides comprehensive local information on the emission of air pollutants, because it results from the collection of point sources and national emission gridmaps at 0.1° (for some regions 0.25°) resolution. Even though the HTAP_v2.2 dataset is not a self-consistent bottom-up database, with activity data defined according to international standards, harmonized emission factors, and emissions gridded with global proxy data, it provides a unique set of emission gridmaps with global coverage and high spatial resolution, including in particular important point sources. The compilation of implied emission factors and per capita emissions for the different world regions using multiple sources provides the regional and national emission inventory compilers with a valuable asset for comparison with their own data for cross checking and analysis which may lead to identification of future improvement options.

This dataset was prepared as emission input for the HTAP community of modellers and its preparation has involved outreach to global and regional climate and air quality modellers (collaborating also within the AQMEII and MICS-Asia modelling exercises). The TF HTAP needed an emission inventory that was suitable for simultaneous and comparable modelling of air quality at the regional scale and at the global scale to

deliver consistent policy support at both scales. The HTAP-v2.2 emission inventory presented in this paper is tailor-made to allow the TF HTAP to fulfil its prime objectives and contribute to a common international understanding of global and regional air pollution and its influence on human health, vegetation and climate. The use of the HTAPv2.2 inventory will substantially help to provide a basis for future international policies because it combines and is consistent with the inventories that are used for regional (EU, US Canada, China) policy analysis and support.

5 Access to the data

The $0.1° \times 0.1°$ emission gridmaps can be downloaded from the EDGAR website on http://edgar.jrc.ec.europa.eu/htap_v2/index.php?SECURE=123 per year, per substance and per sector either in the format of netcdf-files or .txt files. The emissions in the netcdf-files are expressed in $\text{kg substance m}^{-2}\,\text{s}^{-1}$ but the emissions in the .txt are in ton substance/gridcell. For the NMVOC speciated gridmaps we refer to the link on the ECCAD data portal: http://eccad2.sedoo.fr/eccad2/mapdisplay.xhtml?faces-redirect=true.

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Table 1. Sectors in the HTAP_v2.2 inventory (only anthropogenic sources are included) and the corresponding Nomenclature for Reporting (NFR) and the Selected Nomenclature for Sources of Air Pollution (SNAP) codes as spelled out in the EMEP (2002) Reporting Guidelines.

Tag	Description	IPCC level (NFR code)	EMEP SNAP code
htap_1_Aircraft	International and domestic aviation	1.A.3a(i) + (ii)	S8[a]
htap_2_International Shipping	International shipping	1.A.3d(ii)	
htap_3_Power industry	Power generation	1.A.1a	S1
htap_4_Industry	industrial non-power but large-scale combustion emissions and emissions of industrial processes[b] and product use inclusive solvents.	1.A.1b + c, 1.A.2, 1.B.1 + 2, 2.A + B + C + D + G, 3	S3 + S4 + S5 + S6[c]
htap_5_Ground transport	Transport by road, railway, inland waterways, pipeline and other ground transport of mobile machinery[d]. Htap_5 does not include re-suspended dust from pavements or tyre and brake wear.	1.A.3b + c + d(ii) + e	S71 + S72 + S73 + S74 + S75 + S8[e]
htap_6_Residential	Small-scale combustion, including heating, cooling, lighting, cooking and auxiliary engines to equip[f] residential, commercial buildings, service institutes, and agricultural facilities and fisheries; solid waste (landfills/incineration) and wastewater treatment.	1.A.4 + 5 6.A + B + C + D	S2 + S9
htap_8_Agriculture	Agricultural emissions from livestock, crop cultivation but not from agricultural waste burning and not including Savannah burning.	4.A + B + C + D	S10

Notes: [a] S8 (point source) includes local emissions of aircrafts around the airport only below 3000 ft.
[b] Product testing by the manufacturer inside is not considered an emission of the building (htap_6) but taken up under the industry (htap_4). The oil production sector is completely covered in htap_6 and includes the fugitive (evaporative) emissions (mainly NMVOC) during the oil and gas exploration and production and transmission. As such, there are NMVOC emissions along the oil tanker tracks visible under the htap_4 sector).
[c] Note that S34 = S3 + S4 in the TNO-MACC-II inventory (Kuenen et al., 2014). Fuel transformation processes (and refineries) are included here.
[d] The pipeline transport does not include transmission of natural gas and crude oil, because the latter is included in the oil and gas production industry under htap_4 but it does include the transport of refined products (motorgasoline, diesel, liquefied petroleum gas) or goods. The other ground transport includes all mobile (non-stationary) machinery (as used in the agriculture, forestry or construction sector).
[e] For the split-up of SNAP7 into S71 S72, S73, S74 and S75 we refer to the definitions used for the TNO-MACCII inventory documented in Kuenen et al. (2014).
[f] In particular industrial, commercial and/or agricultural buildings can be more extensively equipped with auxiliairy stationary (non-mobile) infrastructure in and around the building (e.g. lifting devices).

Table 2. Comparison of per capita emissions in 2010 for USA, Germany and China from HTAP_v2.2.

Substance	USA	Germany	China
$kg\,SO_x\,yr^{-1}\,cap^{-1}$	32.6	5.2	20.9
$kg\,NO_x\,yr^{-1}\,cap^{-1}$	43.6	14.2	20.8
$kg\,VOC\,yr^{-1}\,cap^{-1}$	43.1	11.9	16.7
$kg\,CO\,yr^{-1}\,cap^{-1}$	148.3	35.6	125.6
$kg\,NH_3\,yr^{-1}\,cap^{-1}$	11.6	7.3	6.7
$kg\,PM_{2.5}\,yr^{-1}\,cap^{-1}$	5.3	1.1	12.2
$kg\,BC\,yr^{-1}\,cap^{-1}$	0.9	0.2	1.3

Table 3. Variables' uncertainties for sector- and country-specific totals per region with qualitative classification using the abbreviations Low (L), Low-Medium (LM), Upper-Medium (UM), and High (H). The legend provides an interpretation of the level Low, Low-Medium, Upper-Medium and High, which is indicatively specified for two groups of countries with two different statistical infrastructures.

	SO_2	NO_x	CO	VOC	NH_3	PM	BC/OC	With legend:	
htap1_air	L	LM	LM	UM	LM	UM	UM	countries with well	Countries with poorly
htap2_ship	L	LM	LM	UM	LM	H	H	maintained statistical	maintained statistical
htap3_energy	L	LM	LM	UM	LM	UM	UM	infrastructure	infrastructure
htap4_industry	LM	LM	LM	UM	UM	LM	LM	L < 15 %	L < 35 %
htap5_ground transport	LM	UM	UM	UM	H	H	H	15 % ≤ LM < 50 %	35 % ≤ LM < 70 %
htap6_residential	LM	UM	UM	UM	H	H	H	50 % ≤ UM < 100 %	70 % ≤ UM < 150 %
htap8_agriculture	UM	UM	UM	UM	H	H	H	100 % ≤ H	150 % ≤ H

Note: The statistical infrastructure of a country determines the uncertainty of the country's emission inventory. Andres et al. (2012) consider under the countries with well maintained statistical infrastructure: the 24 OECD-1990 countries (Australia, Austria, Belgium, Canada, Switzerland, Germany, Denmark, Spain, Finland, France, UK, Greece, Ireland, Iceland, Italy, Japan, Luxembourg, the Netherlands, Norway, New Zealand, Portugal, Sweden, Turkey, and the United States) as well as India (using the British statistical accounting system according to Marland et al. 1999). For the other countries, a larger range in uncertainty is present, for which we refer to Gregg et al. (2008) or Tu (2011) and Olivier (2002). The sector-specific uncertainty of the activity and the quality and representativeness of the controlled emission factors play an important role. The standard range of uncertainty already varies according to the EMEP/EEA (2013) Guidebook's Uncertainties Chapter 5 for the absolute annual total of different pollutants between at least 10 % for SO_2, at least 20 % for NO_x and CO, at least 50 % for NMVOC, an order of magnitude for NH_3, and PM_{10}, $PM_{2.5}$, BC and OC. These considerations have been taken into account to qualitatively indicate a low (L), low medium (LM), upper medium (UM) or high (H) uncertainty for the different sectors and substances.

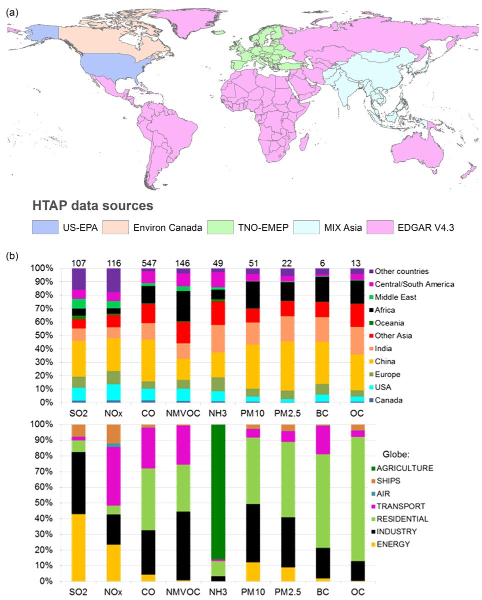

Figure 1. (a) Collection of regional emission inventories (US = EPA, Environ Canada, TNO-EMEP, MIX-Asia, EDGARv4.3) for the global air pollutants and their use for world countries in dataset HTAP v2.2. **(b)** Regional relative contribution to 2010 pollutant emissions (upper panel). Asian emissions have been divided into China, India and other Asia fractions from the MICS database. The region "rest of the world" has been disaggregated into Oceania, Africa, Middle East, Central/South America and other countries making use of the EDGAR v4.3 inventory. Global sector-specific anthropogenic emissions of gaseous pollutants and particulate matter components for the year 2010 (lower panel). Global absolute emissions are reported on top of each bar in Tg species per year. Large scale open-biomass burning is not included in the analysis.

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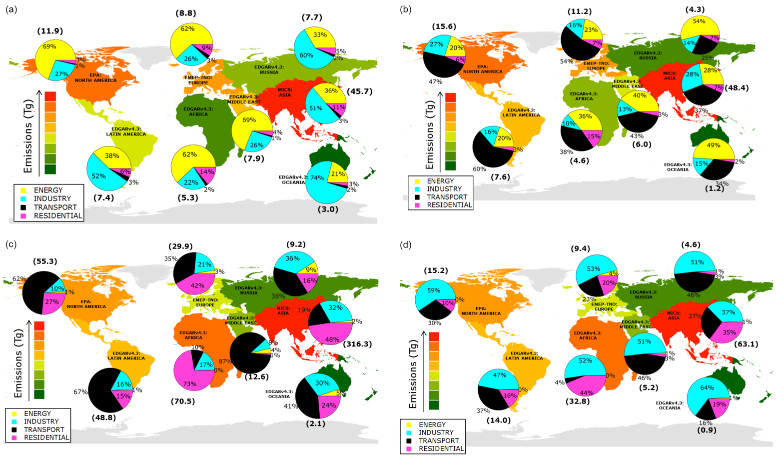

Figure 2. (a) Total Tg SO_2 emissions for 2010 (in brackets) and sector-specific compositionfor world regions. **(b)** Total Tg NO_x emissions for 2010 (in brackets) and sector-specific composition for world regions. **(c)** Total Tg CO emissions for 2010 (in brackets) and sector-specific composition for world regions. **(d)** Total Tg NMVOC emissions for 2010 (in brackets) and sector-specific composition for world regions.

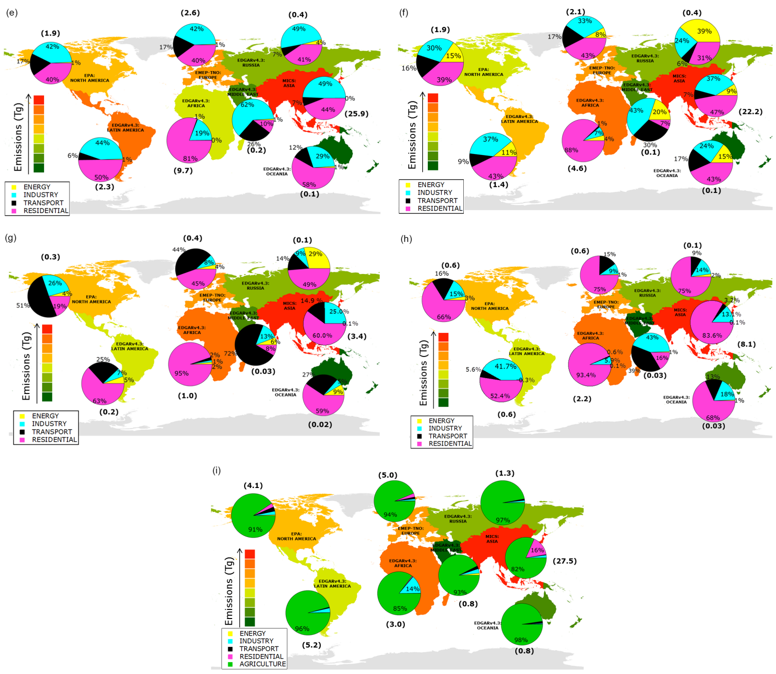

Figure 2. (e) Total Tg PM_{10} emissions for 2010 (in brackets) and sector-specific composition for world regions. **(f)** Total Tg $PM_{2.5}$ emissions for 2010 (in brackets) and sector-specific composition for world regions. **(g)** Total Tg BC emissions for 2010 (in brackets) and sector-specific composition for world regions. **(h)** Total Tg OC emissions for 2010 (in brackets) and sector-specific composition for world regions. **(i)** Total Tg NH_3 emissions in 2010 (in brackets) and sector-specific composition for world regions.

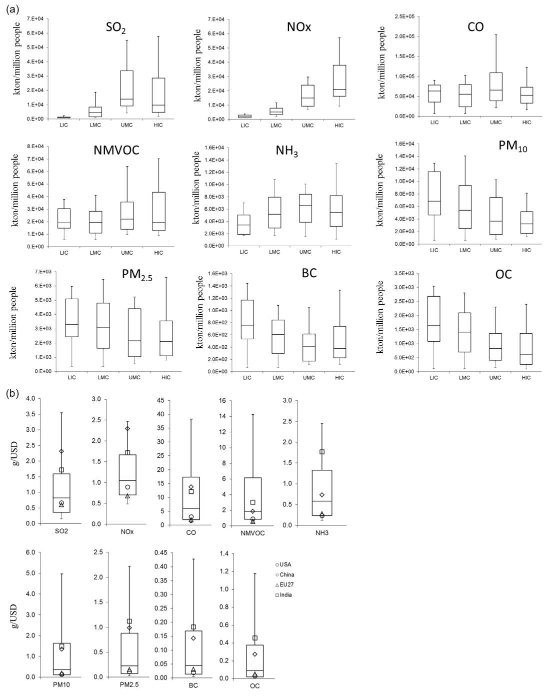

Figure 3. (a) 2010 per capita emissions per substance and per group of countries (in kg $cap^{-1}\,yr^{-1}$): low income (LIC), lower middle income (LMC), upper middle income (UMC) and high income (HIC) with the maximum, and minimum and the percentiles reported in the box plot (10, 50, 90°) and the maximum and minimum in each group of countries. **(b)** Pollutant specific emissions divided by GDP ($g\,USD^{-1}$) for the year 2010. Percentiles are reported in the box plots (10, 25, 50, 75, 90°) together with emission/GDP for specific regions (EU27, USA, China and India).

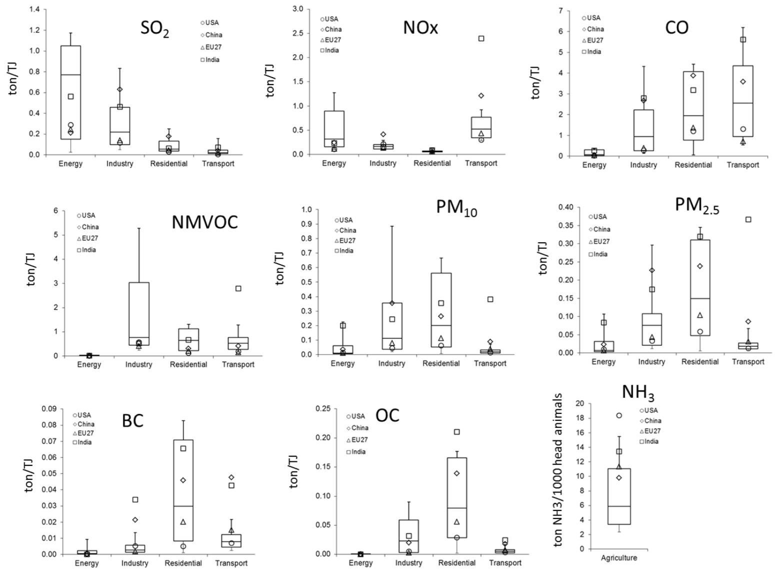

Figure 4. Sector specific implied emissions $(t\,(TJ)^{-1})$ for the year 2010. Percentiles are reported in the box plots (10, 25, 50, 75, 90°) together with implied emission factors for specific regions (EU27, USA, China and India).