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EDGAR v4.3.2 Global Atlas of the three major Greenhouse Gas Emissions for the period 1970-2012.

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Abstract The Emissions Database for Global Atmospheric Research (EDGAR) compiles anthropogenic global emissions and trends based on international statistics and best-available emission factors, for the use in atmospheric models and in policy evaluation. The new version v4.3.2 of the EDGAR emission inventory provides global emission estimates, disaggregated at source-sector level, for the historic period from 1970 (the year of EU's first Air Quality Directive) until 2012 (the end year of the first commitment period of the Kyoto Protocol). The global geo-coverage and continuous time-series are strengths of the EDGAR database, which applies the same methodology and mainly default emission factors to all world countries, in order to achieve comparability and full transparency. Region-specific emission factors are selected, when these are recommended by IPCC (2006) guidelines or when these are justified by robust information on significant differences in economic activities, in customs or in geographical ambient conditions and proven to be more representative than the global average. This database is not only unique in its space-time coverage, but also in the completeness and consistency of the estimated emissions of multiple pollutants: the greenhouse gases (GHG), air pollutants and aerosols. This publication documents the first part of the EDGAR v4.3.2 emissions database focusing on emissions of the three major greenhouse gases of CO_2, CH_4 and N_2O, from human activities apart from the land-use, land-use change and forestry (LULUCF) sector (including forest and savannah burning). Unlike the activities of the LULUCF sector, which are typically estimated top-down from less certain land-use observations, all these activities are estimated bottom-up from standard annual statistics of fuel, products, waste, crops or livestock. We present country-specific emission totals and analyse the trends and variations in emissions of the largest emitting countries together with the EU in more detail, to uncover the effect of changes in human activities with time on each of the gases. The GWP-100 weighted global total GHG emission trend is predominantly determined by the global CO_2 trend and in particular, by fuel markets trends, geopolitical changes and financial crises rather than population changes. We also evaluate the uncertainty in emissions for different sectors and three groups of countries (the OECD countries of 1990, the countries with economies in transition in 1990 and the remaining non-Annex I countries). Even though large progress has been made on emission inventory compilation, the uncertainty in global total GHG emissions has not decreased, because of the increasing share of emissions from countries with less developed statistical infrastructure and secondly the decreasing share of emissions from the activities (e.g. coal power plants) for which relatively accurate information is available. Finally, we discuss changes in geospatial distribution with a focus on hot spots and megacities using gridded information. Data is presented online for each source category with annual and monthly global emissions grid-maps of 0.1°x0.1° resolution and can be freely accessed from the EDGAR website http://edgar.jrc.ec.europa.eu/overview.php?v=432&SECURE=123 (DOI: https://data.europa.eu/doi/10.2904/JRC_DATASET_EDGAR).

1. Introduction

The United Nations Framework Convention on Climate Change (UNFCCC, 1992) was ready to be signed barely two years after the first qualitative assessment report of the Intergovernmental Panel on Climate Change (IPCC, 1990). Within the next 2 years, it already entered into force, on March 21, 1994. With the aim to "*stabilize GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*", this treaty was amended with several legally binding commitments for limiting GHG emissions. There are:

- the Kyoto Protocol (KP) of UNFCCC (1997), signed in 1999 and in force since 2005 with binding targets in 43 countries for the first commitment period[1], and
- the Paris Agreement (PA) of UNFCCC (2015), adopted on December 2015 by 194 countries and entered into force less[2] than one year later on 4 November 2016

An essential component of the UNFCCC framework is the collection of nationally reported inventories and information on these GHG emission inventory time series. At the time the UNFCCC was drafted, the 24

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[1] The targets under the second commitment period were included in the Doha Amendment, which has been mainly ratified by countries without a target and which has not yet entered into force.

[2] Ratified by 153 Parties out of 197 (status of 15 July 2017). The USA withdrew on 1 June 2017.

members of the OECD in 1990 and 16 other European countries and Russia were considered liable of "*the largest share of historical and current global emissions of GHG*" and as such taken up in Annex I to the UNFCCC. These Annex I countries are required to demonstrate their efforts in reducing anthropogenic emissions of the KP GHG[3]. Annually the Annex I countries and the EU submit complete inventories of GHG emission sources and sinks from the 1990 base year[4]. Their inventories are all annually reviewed to ensure that they are transparent, complete, comparable, consistent and accurate.

Other countries are encouraged to submit their GHG inventories as part of their National Communications and Biennial Update Reports (BUR). To date 150 countries have submitted one or more National Communications, including a chapter with a summary of the GHG inventory. The original requirements for the GHG inventories of non-Annex I countries were emissions of the 3 main GHGs (CO_2, CH_4 and N_2O) for one year (1990 or 1994). No specific documentation of inventory was required, and they were reviewed only briefly as part of the national communication review. However, the PA requests to submit every 2 years BURs[5], which are subject to international consultation and analysis. Figure 1 presents the year of latest submission with the inventory year for which data is available to the UNFCCC. Aside of the Annex I countries, which are obliged to yearly report updated emission inventories, the information on emission inventories is for quite some countries dating more than 10 years ago, with the year of the inventory that is for most South-East Asian countries between 2004-2007 and for most African countries between 2000-2003.

Due to the different requirements for the different world countries' inventories, and different methods used to estimate emissions, the collection of national reports/ communications do not provide a complete, consistent and comparable global dataset, which can be used to understand the global budgets of the most important GHG emissions and their resulting impacts on climate. The scientific community produced global inventories: such as the Global Carbon Project (GCP) (Le Quéré et al., 2016), the Carbon Dioxide Information Analysis Centre (CDIAC) (Boden et al., 2017; Andres et al., 2014) and the Emissions Database for Global Atmospheric Research (EDGAR) (Olivier et al., 2016a,b). In the Fifth Assessment report (AR5) of IPCC Working Group III (IPCC, 2014) the reported GHG (fig. SPM.1) combines CO_2 emissions related to fossil fuel use from IEA (2012) with other CO_2 emissions sources and non-CO_2 emissions from EDGAR 4.2 FT2010 (JRC/PBL, 2012). Figures TS.2 and TS.4 (IPCC, 2014) shows the growing uncertainty of the global emissions and the large range of per capita emissions for the different country income groups. In addition, Lamarque et al. (2010) compiled a dataset of

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[3] The KP GHG are defined as the GHG covered by the first commitment period of the Kyoto Protocol: CO_2, methane (CH_4), N_2O, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and SF_6. Under the second commitment period of the Kyoto Protocol, also NF_3 is included as GHG.

[4] For some economies in transition another year, such as 1988 or 1989 can be chosen under UNFCCC as base year.

[5] The first BUR submitted should cover the inventory for the year no more than 4 years prior to the submission data, and subsequent BURS should be submitted every 2 years, but flexibility is given to least developed countries and small island developing states.

historical gridded emissions of reactive gases and aerosols, which contains also CH_4 for the Climate Model Intercomparison Programme CMIP5 (for AR5). These global emission inventory efforts are threatened with discontinuity: CDIAC ceases operations in September 2017 and the emissions work of Lamarque et al. (2010) was only after 5 years taken over by ORNL, building newly the Community Emissions Data System (CEDS) of Hoesly et al. (2017).

The inventory group of IPCC (2006) produced GHG inventory guidelines that include international "best practices" and are an extensively described international standard. Countries can choose between different methodological levels of detail to estimate their emissions and emission trends. More advanced and detailed methods (the so called tier 2 or tier 3) generally have to be applied to categories which together cover more than 95% of the emissions. The UNFCCC reporting system thus produces series of national inventories, which cover all sources coded according to the IPCC (2006) guidelines, but are still heterogeneous as individual countries can select different tiers or different emission factors for each emission source.

The EDGAR inventory estimates the country emissions using the same tier method for all countries and consequently gives as such a global emissions estimates that have a more homogeneous country-specific breakdown. Even though significant progress in inventory compilation has been made and as a consequence uncertainties in particular in the inventories of Annex I countries can be assumed to have declined, the overall uncertainty of the global total has become more uncertain over time because of the increasing contribution from non-Annex I countries, as shown in Figure 2. Whereas the share of emissions from Annex I countries was more than 60% in 1990, by 2012 more than 60% of the emissions are from non-Annex I countries.

The need for measurable, reportable and verifiable (MRV) mitigation commitments and actions was already recognised in the Bali Action Plan of the 13th Conference of Parties (COP13, 2007) and emphasised at COP21 (2015) where the PA required countries to track their progress towards their long-term goal, using a robust transparency and accountability system. Figure 2 presents the share of global emissions that is covered under the KP (30%) and the PA (80%). The 80% share of global total emissions covered by the PA allows to target with the nationally determined contributions (NDC) gradual reductions in a much larger emissions budget than the KP was able to target. However, as discussed above, this PA emissions budget is less well-known and consequently a global picture and a reference for monitoring the emission levels from all world countries is needed. In 2023 a global stocktake is foreseen to track the progress of the collective efforts to reduce the emissions as promised under the NDCs. Comprehensive information on global emissions, consistently compiled for all world countries available from EDGAR v4.3.2 can help to assess and build trust in the effectiveness of the NDCs. Moreover the country estimates of EDGAR v4.3.2 can also help countries with less developed statistical infrastructures to compile their inventories.

With the transparency framework for independent verification, the PA has made a first step towards independent verification, while also bridging the gap between the Working Group III of IPCC's Assessment Report and the IPCC Task Force on National Greenhouse Gas Inventories. The verification process under the KP consisted of procedural checks of the bottom-up inventory compilation, checking the completeness of activity data, representativeness of emission factors, consistency between the newly submitted inventory time series and the previous submissions, but they are self-reported and all based on similar data sources. The PA calls for a "*transparency framework*" that shall build upon and eventually supersede the MRV system to build thrust with an independent verification system, using other data sources of a different nature, such as atmospheric GHG concentration measurements.

To support both science and policy making within this GHG verification, it will be important to have emission estimates using consistent source allocation covering the entire globe and using comparable methodologies for all countries. This paper presents the methodologies and key results of the global inventory of CO_2, CH_4 and N_2O calculated consistently for all world countries by the Emissions Database for Global Atmospheric Research (EDGAR), version v4.3.2. EDGAR v4.3.2 makes use of the IPCC guidelines (IPCC, 2006) and provides consistent estimates of the global anthropogenic emissions and emission trends, based on publicly available statistics, preferably of international organisations. The EDGAR v4.3.2 inventory covers sector- and country-specific time series of 1970-2012 with monthly resolution as well as global grid-maps at a spatial resolution of 0.1°x0.1°, ready to be used in atmospheric models.

This publication focuses on the three major GHG emission components, describing the methodology, emission sources, activity data and emission factors. The non-CO_2 GHG emissions are also provided to the IEA for the annual publication of emissions from fuel combustion (Olivier and Janssens-Maenhout, 2016b). The methodology and activity data are also used to estimate corresponding gaseous and particulate air pollutant emissions, as part II of the EDGAR v4.3.2 release (Janssens-Maenhout et al., 2017). These follow up the EDGAR v4.3.1 inventory used by Crippa et al. (2016a) and the v4.tox1 inventory used by Muntean et al. (2014). For the NMVOC speciation we refer to Huang et al. (2017).

Section 2 presents the original statistical activity data and emission factors per source category. In section 3 we analyse the time series with qualitative evaluation of the uncertainty, and then perform an inter-comparison with other inventories. The resulting grid-maps are discussed in section 4 and the concluding section 5 summarises the strengths and weaknesses of the EDGAR v4.3.2 emissions inventory.

2. Methods

2.1 Technology-based emission calculations

The first version of the Emissions Database for Global Atmospheric Research (EDGAR v2) was published by Olivier et al. (1996). Since then, several updated versions (Olivier, 2002) were released (EDGAR-HYDE, EDGAR v3.2, EDGAR 3.2 FT2000, EDGAR v4.2 as documented at http://edgar.jrc.ec.europa.eu/index.php#), driven by the development of scientific knowledge on emission generating processes and scientists' and policy-makers' needs for more recent information. Taking advantage of these, the new online version, EDGAR v4.3.2 incorporates a full differentiation of emission processes with technology-specific emission factors and additional end-of-pipe abatement measures[6] and as such updates and refines the emission estimates.

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[6] The specification of the combustion technology and its end-of-pipe abatement is more important for air pollutants and aerosols than for greenhouse gases. CO_2 combustion emissions are fuel-determined and carbon

The emissions are modelled based on latest scientific knowledge, available global statistics, and methods recommended by IPCC (2006). Official data submitted by the Annex I countries to the UNFCCC and to the Kyoto Protocol are used to some extent, particularly regarding control measures implemented since 1990 that are not described by international statistics. However, emissions reported by countries are not used in order to maintain cross-country consistency and impartiality.

Emissions (*EM*) from a given sector *i* in a country *C* accumulated during a year *t* for a chemical compound *x* are calculated with the country-specific activity data (*AD*), quantifying the activity for sector *i*, with the mix of *j* technologies (*TECH*) and with the mix of *k* (end-of-pipe) abatement measures (*EOP*) installed with share *k* for each technology *j*, the emission rate with uncontrolled emission factor (*EF*) for each sector *i* and technology *j* and relative reduction (*RED*) by abatement measure *k*, as summarized in the following formula:

$$EM_i(C,t,x) = \sum_{j,k}\left[AD_i(C,t) * TECH_{i,j}(C,t) * EOP_{i,j,k}(C,t) * EF_{i,j}(C,t,x) * \left(1 - RED_{i,j,k}(C,t,x)\right)\right] \tag{1}$$

The activity data vary strongly and include consumed energy (*TJ*) of a particular fuel type, the amount (*ton*) of products manufactured, the number of animals elevated or the area (*ha*) and yield (*ton*) of cultivated crops. The technology mixes, (uncontrolled) emission factors and end-of-pipe measures, are determined at different levels: country-specific, regional, country group (e.g. Annex I/ non-Annex I), or global. CO_2 emissions primarily depend on the carbon content of the fuel in the combustion process, while CH_4 depends also on fermentation processes and the total mass decomposed. Technology-specific emission factors are used to take into account the different infrastructures (e.g. different distribution networks) or different management processes, while abatement measures model explicitly e.g. the CH_4 recovery at country level. EDGAR v4.3.2 uses international annual statistics (avoiding inaccuracies of monthly or daily fluctuations and hold-ups of fuels or products in the accounting) and consequently calculates country inventories with yearly time steps.

The sector-specific total emissions of substance *x* for country *C* in year *t* are then distributed in time and space using sector- and even technology-specific monthly shares *m* and spatial proxy datasets *f*. The proxy datasets are expressed in function of coordinates (longitude, latitude) weighted at country level and with the Heaviside function equalling 1 when the grid cell belongs to the country area according to the following formula:

$$em_i(lon,lat,t,x) = EM_i(C,t,x)\frac{m_{i,j}(C)}{\sum\limits_{k=1,..12} m_{i.,j}(C)}\frac{f_{i,j}(lon,lat,t)}{\sum\limits_{lon,lat}\left(f_{i,j}(lon,lat,t)\cdot H(C,lon,lat)\right)}$$

$$with\ H(C,lon,lat) = \begin{cases} 1\ \ if\ \ (lon,lat)\ within\ C \\ 0\ \ if\ \ (lon,lat)\ outside\ C \end{cases} \tag{2}$$

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capture and storage is not yet at operational level implemented and not considered here. However abatement is considered for e.g. CH_4 recovery of coal mines and technology and end-of-pipe abatement are important for both adipic and nitric acid plants. Finally management of crop cultivation (e.g. for rice) or of manure are accounted for by technology-specific emission factors for CH_4 and N_2O.

While the monthly shares are more specified in a generic way (only varying with the latitudinal region and with the sectors), the spatial proxy datasets take into account point-source information at sub-sector level (facilities) that varies from year to year.

2.2 Definitions of source sectors

The sources are defined according to the sectors and codes used in the 1996 IPCC guidelines, Chapter 1 of Vol. 1 Reporting Instructions (IPCC, 1996) but with conversion to the new 2006 IPCC guidelines, Chapter 8 of Vol.1 Guidance and Reporting (IPCC, 2006a)[7]. All sectors based on fuel or product consumption statistics are considered. The Land-Use, Land-Use Change and Forestry sector is not included, because the sources and sinks due to carbon stock changes considered in this sector are currently derived from geographical information and/or remote sensing data. As such, large-scale biomass burning (including forest fires, Savannah burning, grassland and woodland fires) is not included in EDGAR v4.3.2 but can be obtained from GFED (Van der Werf et al., 2010), GFAS (J. Kaiser et al, 2012) or FINN (Wiedinmeyer et al., 2011). For the emissions sources and sinks due to living biomass remaining biomass in forests (not wooded cropland), we refer to Petrescu et al. (2012). All activity data for the EDGAR v4.3.2 version are mostly taken from international statistics, checked for completeness and consistency, removing outliers (clerical errors such as wrong unit) and holes (missing single year) with a linear interpolation of the previous and the following year.

Being a global emissions inventory, it is based on international statistics such as those of IEA (2014) and FAOSTAT (2014) rather than regional offices, such as EuroStat or national statistical bureaux. The latter mostly report to IEA or FAO, who then control the data quality. For the two largest emitting countries, China and USA, national data from the Chinese Bureau for statistics and the US Energy Industry Administration respectively are consulted to assess and gap fill the activity data with consumption of fuels (fossil and bio) and of products (mainly metals, non-metallic minerals such as cement, chemicals, solvents). For Europe, only the biofuel statistics of EuroStat showed to be updated faster than the IEA fuel statistics for EU28. Where possible, GHG emission factors are selected from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) to ensure consistent and complete time-series, which are comparable across countries. Annual reports of Annex I countries to the UN Convention on Climate Change (UNFCCC, 2014) and National Communications and Update Reports from large non-Annex I countries with emerging economy are also consulted to assess the representativeness of default emission factors for these regions. In addition, Clean Development Mechanism projects are taken into account in developing countries to account for abatement measures of CH_4 and N_2O emissions via CH_4 recovery from coal mining and landfills and N_2O reduction in nitric and adipic acid production. Table 1 gives an overview for the 3 major greenhouse gases of the major emission sectors (with respectively the 1996 and 2006 common reporting format codes), which are described in more detail in Appendix A of the IPCC (2006b) Guidelines.

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[7] The IPCC (1996) reporting codes allow intercomparability and transparency of EDGAR v4.3.2 versus previous EDGAR versions.

2.3 Data sources for the emission time series

Population statistics: the annual total population (both sexes) by country from the yearly revised world population prospects of UN DP (2015) provides consistent time-series 1950-2015 (used from 1970 onwards) for 228 world countries[8]. With the country-specific percentage of population at mid-year residing in urban areas from the world urbanisation prospects of UN DP (2014), two additional time series, one for urban population and one for the counterpart of rural population were derived for each of the 228 countries.

Energy statistics: Data for the energy content (*TJ*) of annual fossil fuel consumption in 138 countries (as spelled out in Table S1 of the Supplementary) was taken from the IEA energy balance statistics (IEA, 2014) for OECD and Non-OECD countries for 1970-2012. Where data in 1970 were missing, the 1971 data were used instead. This dataset comprises 64 fuel types (specified in Table S2 of the Supplementary) and 94 fuel use activities that are mapped with this detail to EDGAR activity codes (cfr. Table S3 of the Supplementary). For hard coal and brown coal data for 1970-1978 were split using the 1979 shares of the fuel types in order to keep fuel type consistency and to obtain complete time-series of the different types of coal (characterised with different emission factors). For the countries of the former Soviet Union and former Yugoslavia the pre-1990 data was allocated to the countries using the same sector-specific country shares of the new countries from 1990. For the full time-series we used “Serbia-Montenegro” in the dataset, which includes Kosovo (reporting statistics separately since 2000) and Montenegro (with reported statistics since 2005). For another 62 countries, the IEA data provides only the lumped sum of the regions ‘Other America’, ‘Other Africa’ and ‘Other Asia’. The sector- and fuel-specific activity data for these 3 regions have been disaggregated over time following the IEA definition of these regions and using the total production and consumption figures per country of coal, gas and oil from energy statistics reported by the US Energy Information Administration (EIA, 2014).

The biofuel input for most OECD countries is based on the final consumption of biogasoline (bioethanol), biodiesel and other liquid biofuel categories of IEA (2014), allocated to road transport and blended with fossil petrol, diesel or LPG. For Iceland, Israel and Mexico this is supplemented with the biofuel consumption reported by EIA (2013). For Japan, Argentina, Brazil, China, India, Indonesia, Malaysia, Peru, Philippines and Thailand the biofuel data are supplemented with the data from USDA (2014).

Fossil fuel production statistics: for solid fuel production and transmission, hard coal and brown coal production data have been separated into surface and underground mining based on the World Coal Association (2016). For gas transmission and distribution, the leakage rate is assumed proportional to the length of the pipelines and depends on its construction material (grey cast iron, steel, polyethylene or polyvinylchloride). While gas transmission through large pipelines is characterised with relatively small country-specific emission factors of Lelieveld et al. (2005), much larger and material-dependent leakage rates of IPCC GL (2006) were assumed for gas distribution. Pipeline length and 2012 material statistics are taken from reports on Europe by the Eurogas (2010) report and Marcogaz (2013) technical sheet, UNFCCC National Inventory Reports (2014) and

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[8] The way countries are presented in the dataset does not imply any opinion of the authors on the legal status of any of the territories.

supplemental data from CIA (2008, 2016). The total amount of natural gas flared (sometimes including gas vented) for most countries from 1994 onwards are primarily based on the amount of gas flared determined from the NOAA satellite observation of the intensity of flaring lights by Elvidge et al. (2009). For the years before 1994 and for other countries emissions or their trends were calculated based on the difference in fuel produced and fuel sold from IEA supplemented with trends from CDIAC (Andres et al, 2014); EIA, 2014 and UNFCCC (2014) National Inventory Reports.

Methane (CH_4) emission factors for coal mining are based on average depths of coal production and include post mining emissions, following IPCC recommendations and the EMEP/EEA (2013) Guidebook. According to Peng et al. (2016) and Liu et al. (2015), Chinese underground coal mines are characterised by low quality coal and, as such, low EF, corresponding to the lower end of the range of EFs recommended by EMEP/EEA for coal mines in Europe. The average emission factor, used in the earlier EDGAR v4.2 increased the CH_4 emission rates faster than observed from satellite observations (Bergamaschi et al., 2013). Moreover, there are many smaller scale mines in China, which seem to flood after closure. CH_4 recovery from coal mining was estimated following IPCC (2006) for the 11 countries with largest coal mining in the past. These are in decreasing order of the share of the total CH_4 emission from this sector: Czech Republic (60%), Spain (36%), Poland (33%), USA (29%), UK (25%), Germany (24%), Ukraine (16%), Australia (15%), China (9%), Russia (3%), Kazakhstan (2%). Abandoned and closed mines are accounted for with very different shares to the total CH_4 emissions in 2012 from coal mining in UK (with 24%), Romania, China, USA, Czech Republic, Germany and Ukraine (0.3%). Emission factors for oil and gas production, transport and distribution from the 2006 IPCC guidelines are supplemented with data from UNFCCC (2014). The CH_4 emission factor for venting and flaring has been derived from country specific data reported to UNFCCC (2014) with the average value used as the global default, applied to all other countries. The CO_2 emission factor excludes indirect emissions through gas venting.

Industrial processes statistics: Production data for the CO_2 sources cement, iron and steel, non-ferrous metals and various chemicals are based on Commodity Statistics of UN STATS (2014) often supplemented for recent years by USGS (2014). CO_2 from cement production is based on the Tier 1 emission factor for clinker production, whereas cement clinker production is calculated from cement production reported by USGS (2014). The implied clinker to cement ratio is based on either clinker production data from UNFCCC reporting (Annex I countries) and the China Cement Almanac, or ratios from WBCSD-CSI (2015). Iron and steel production is further split into technologies (basic oxygen furnace, open hearth, electric arc furnace) using data of WSA (2014). For other CO_2 sources such as production of lime, soda ash, ammonia, ferroalloys and non-ferrous metals, we combine USGS (2014) data and data reported to the UNFCCC (2014). Primary aluminium production statistics per country from UN are combined with smelter types (Horizontal and Vertical Stud Söderberg technologies as well as Centre Work, Point Feed, and Side Work Prebake technologies) characterised by Aluminium Verlag (2007) and IAI (2008). For primary magnesium production and die-casting global consumption was derived from production statistics from USGS (2014) and IMA (1999) and reported country-specific die-casting companies. UN STATS (2014) Commodity Statistics are also applied to estimate the emissions from bread production, while for paper, wine and beer we use FAO (2016c,d) production data.

For the CO_2 sources from industrial production of silicon and calcium carbide, glyoxal and other chemical bulk products (acrylonitrile, black carbon, ethylene, ethylene oxide, methanol, and vinyl chloride) for which no

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international statistics were available, UNFCCC (2014) is used, although limited to Annex I countries. Interpolations and extrapolations were only done to gap-fill single years with missing reported data in the time series 1970-2012, making use of the average of the previous and following years. Data of IFA (2015) are used for urea production, which accounts the fossil carbon in CO_2 from ammonia production, following IPCC (2006). Data of FAOSTAT (2014) are used for production of pulp, meat and poultry. Ammonia production data are taken from USGS (2014).

For the N_2O sources of nitric acid, adipic acid and caprolactam, production as well as abatement data from 1990 onwards are based on UNFCCC (2014) and SRIC (2008). For nitric acid production in 1970, only old technology is assumed, with a gradual change in technology by 1990 into high pressure plants in non-Annex I countries and a mix of low and medium pressure plants in Annex I countries, in line with reported emissions to UNFCCC (2014).

Solvents statistics: For CO_2, the national inventory reports of UNFCCC indicate a small amount of CO_2 emission per ton paint applied, or per ton degreasing and dry cleaning product or other chemical product used. Activity data for paints, glues and adhesives, degreasing products, pesticides and vegetal oil are found in the UN Commodity statistics and supplemented with the UN Comtrade (2016) statistics details. Activity data 1990-2012 for other solvent use from UNFCCC (2014) was integrated for Europe, USA, Australia and New Zealand and Japan and linearly extrapolated backwards in time. N_2O use as an anaesthetic and in aerosol spray cans is assumed proportional to the population. The average per capita N_2O use reported by Annex I countries to UNFCCC (2014) was used as region-specific default.

Agricultural statistics: Following IPCC (2006) methodology we apply FAO crop and livestock data and IPCC (2006) emission factors for CO_2, CH_4 and N_2O. Livestock numbers for buffalo, camels, dairy and non-dairy cattle, goats, horses, swine, sheep, mules and asses and for poultry (turkeys, geese, chickens and ducks) are taken from FAOSTAT (2014). These all contribute to manure and to enteric fermentation, except poultry that only produce manure. Historic data for countries of the former Soviet Union (1970-1990), Yugoslavia (1970-1992), Belgium and Luxemburg (1970-1999), Czechoslovakia (1970-2012) and Ethiopia and Eritrea (1970-2012) are split up, using the share in the first available year of statistics for the individual countries. Serbia and Montenegro data are merged from 2006 onwards, Sudan data are gap-filled for 2012-2014 with data of 2011 and the chicken data for Switzerland were corrected in 2007. For enteric fermentation by cattle, country specific methane emission factors are calculated following IPCC methodology (IPCC, 2006), using country specific milk yield (dairy cattle) and carcass weight (other cattle) trends from FAO (2007) to estimate the trends in the emission factors. For other animal types, regional emission factors from IPCC (2006) are used.

Livestock numbers are combined with estimates for animal waste per head to estimate the total amount of animal waste produced. Nitrogen excretion rates for cattle, pigs and chicken in developed countries are derived from the CAPRI model[9] for Europe (Leip et al., 2007) and for all other countries and animal types IPCC (2006) values are used. The trend in carcass weight was used to determine the trend in nitrogen excretion over time. Shares of

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[9] www.capri-model.org

different animal waste management systems are based on regional defaults provided in IPCC (2006) and regional trend estimates for diary and non-dairy cattle for the fractions stall-fed, extensive grazing and mixed systems from Bouwman et al. (2005). CH_4 emissions from manure management are estimated by applying default IPCC emission factors for each country and temperature zone. Livestock fractions of the countries are calculated for 19 annual mean temperature zones for cattle, swine and buffalo and three climates zones for other animals (cold, temperate, warm). N_2O emissions from manure management are based on distribution of manure management systems from Annex I countries reporting to the UNFCCC, Zhou et al. (2007) for China and IPCC (2006) for the rest of the countries.

The total area for rice cultivation, obtained from FAOSTAT (2014), is split between the different agro-ecological land-use types (rain fed, irrigated, deep water and upland) using data from IRRI (2007). Methane emission factors for the various production land-uses are taken from IIASA (2007).

N_2O emissions from the use of animal waste as fertiliser are estimated taking into account both the loss of nitrogen that occurs from manure management systems before manure is applied to soils and the additional nitrogen introduced by bedding material. N_2O emissions from fertiliser use and CO_2 from urea fertilisation are estimated based on IFA and FAO statistics. The N_2O emission factor for direct soil emissions of N_2O from the use of synthetic fertilisers and from manure used as fertilisers and from crop residues is taken from IPCC (2006), that updated the default IPCC emission factor in the IPCC Good Practice Guidance (2000) with a 20% lower value.

CO_2 emissions from liming of soils are estimated from Annex I country reports to the UNFCCC and on the use of ammonium fertilisers for other countries from FAOSTAT (2014), as liming is needed to balance the acidity caused by ammonium fertilizers. Areas of cultivated histosols are estimated by combining the FAO climate and soil maps (FAO Geonetwork, 2011) with the RIVM land-use map (Goldewijk et al., 2007). Different N_2O emission factors are applied to tropical and non-tropical regions. Nitrogen and dry matter content of agricultural residues are estimated from the cultivation area and yield for 24 crop types (2 types of beans, barley, cassava, cereals, 3 types of peas, lentils, maize, millet, oats, 2 types of potatoes, pulses, roots and tubers, rice, rye, soybeans, sugar beet, sugar cane, sorghum, wheat and yams) from FAOSTAT (2014) and using emission factors of IPCC (2006). The fraction of crop residues removed from and burned in the field is estimated using data of Yevich and Logan (2003) and UNFCCC (2014) for the fraction burned in the field by Annex I countries.

Indirect N_2O emissions from leaching and runoff of nitrate are estimated from nitrogen input to agricultural soils as described above. Leaching and runoff are assumed to occur in all agricultural areas except non-irrigated dryland regions, which are identified with maps of FAO Geonetwork (2011). The fraction of nitrogen lost through leaching and runoff is based on the study of Van Drecht et al. (2003). The updated emission factor for indirect N_2O emissions from nitrogen leaching and run-off from the IPCC (2006) guidelines is selected, while noting that it is 70% lower than the mean value of the 1996 IPCC Guidelines and the IPCC Good Practice Guidance (IPCC, 1997, 2000).

Solid Waste product statistics: The amount of organic solid waste in landfills is determined by 3 key parameters: (a) Municipal Solid Waste (*MSW*) generated per year (*kg/cap*), (b) fraction f of total solid waste that is deposited on landfills, and (c) fraction of Degradable Organic Carbon (*DOC*) in the *MSW*. The per capita MSW generation rate (for 2000) and the fraction MSW disposed, incinerated and composted are based on the specification for 75 countries by IPCC (2006) and updated as outlined below. For 151 other countries, the MSW generation rate and fraction disposed are assumed the same in comparable countries of the same region (with the world divided into 4 Asian regions, 5 African regions, 4 European regions, 2 regions in Oceania, 3 American regions and the Caribbean) and within the same income class (within the same GDP range). The IPCC Waste Model also provides for these 19 regions the average weight fraction DOC under aerobic conditions, which has been used as the default for all countries. For Annex I countries these three parameters have been updated for the period 1990-2012 where UNFCCC (2014) have reported country-specific information on the parameters (within the expected range). The national total *MSW* reported to UNFCCC (2014) correlates best with total population (*POP*) for industrialised countries and with urban population in case of developing countries. As such the total *MSW* is calculated using the respective correlation for each country according to whether it is industrialised or developing. The *DOC* fraction of the total *MSW* landfilled is direct input to a First Order Decay (FOD) model for CH_4 generation, described according to IPCC (2006) Guidelines by formula (3), and using default parameters for the Methane Correction Factor (*MCF*), the decomposition constant (*k*) and the Oxidation Factor (*OX*).

$$EM_i(C,t,CH_4) = \left[\left(W(C,t) + \left(1 - e^{-k(C,t-1)}\right) . W(C,t-1)\right) . e^{-k(C,t)} - R(C,t)\right] \left(1 - OX(C,t)\right)$$
$$\text{with } W(C,t) = \frac{1}{3} . f . MSW(C,t) . POP(C,t) . DOC(C,t) . MCF(C,t) \qquad (3)$$

The *MCF* is characterised by the type of landfill: managed aerobic or anaerobic, unmanaged deep or shallow. Decomposition under anaerobic conditions is assumed to occur for 50% in the countries apart from 12 Annex I countries, which are corrected to a country-specific estimate based on their UNFCCC (2014) reports. The *MCF* default is calculated as a linear variation between 0.4 and 1.0 with the urban population share and is corrected with reported data from UNFCCC (2014) reports of Annex I countries for 1990-2012 and linearly extrapolated backwards in time. The decomposition constant *k* is inversely proportional to the half-life value of the *DOC* and depends on climatic conditions, so that the exponential decaying reaction varies between 0.96 and 0.67. The IPCC Waste Model specifies default *k* values for 4 climatic zones (dry temperate, wet temperate, dry tropical and moist/wet tropical) are applied, except for the Annex I countries where the nationally measured value is selected instead. As Oonk (2010) indicated, the *k*-value of CH_4 generation half-life or biodegradation rate is a less sensitive parameter in the emissions calculation with the FOD than the oxidation of CH_4, for which data are missing. *OX*, which depends in part on the top layer design of the landfill and on climatic conditions, is by default zero and is only updated to a value between 3% and 10% for those Annex I countries which reported this oxidation in their national inventory report (UNFCCC, 2014). The volumetric fraction of CH_4 in generated landfill gas is assumed constant and equal to 50% for all world countries. Finally, the amounts of recovered CH_4 *R* (used or flared) are subtracted from the gross CH_4 emissions, only for Annex I countries, who reported this to UNFCCC (2014) and for 23 non-Annex I countries with CDM projects reported by the UNEP Risø Centre (2011). It is evident that these estimates are relatively uncertain, even though the source is declining considerably.

Wastewater statistics: The effect wastewater discharges have on the receiving environment depends on the oxygen required to oxidize soluble and particulate organic matter in the water and as such the Chemical Oxygen

Demand (*COD*) and Biochemical Oxygen Demand (*BOD*) are used to characterise the quality of industrial and domestic wastewater. The total organically degradable material in wastewater for industry (*TOWi*) is estimated as kg *COD* /yr with country-specific data on meat (FAO, 2016a), sugar (FAO, 2016b), pulp (FAO, 2016c), ethyl alcohol (UN SD, 2016; RFA; 2016) and organic chemical (31 chemicals[10]) production. IPCC (2006c) default values for wastewater generation and CODs are used to derive TOWs for each industry type. For domestic and commercial organically degradable material in wastewater (*TOWd*) we used IPCC (2006) with default values for kg *BOD* /yr for rural and urban (low and high-income) areas. Country-specific shares of low-income and high-income urban population are taken from UNHABITAT (2016a, 2016b) and World Bank (2016). Different wastewater treatments are specified with technology-specific CH_4 emission factors. For domestic wastewater the sewer to waste water treatment plants (WWTP), sewer to raw discharge, bucket latrine, improved latrine, public or open pit and septic tank are distinguished. Regional or country-specific default fractions for 2000 are from IPCC (2006). In addition, country-specific shares of different wastewater treatment systems representing improved sanitation over time are taken from Van Drecht et al. (2009) and Doorn and Liles (1999). For industrial CH_4 emissions, on-site treatment in WWTP, sewer with and without city-WWTP, and raw discharge are distinguished with shares and regional emission factors from Doorn et al. (1997).

For N_2O, nitrogen in the effluent discharged to aquatic environments (N-effluent) was calculated following IPCC (2006) for each country, as a function of the human population and annual per capita protein consumption data from FAO (2016a,b). Other parameters are kept constant: the nitrogen fraction for protein is 0.16 kg N /kg protein (IPCC (2006) default values), the factor for non-consumed protein entering wastewater is 1.25 for the USA and 1.1 for all other countries, and the factor for industrial and commercial co-discharged protein into the sewer system is 0.25 for industrial N-effluent and 1.00 for domestic and commercial N-effluent.

Other waste sources are incineration, with activity data from UNFCCC (2014) and IPCC (2006), extrapolated assuming a fixed ratio to landfilling, and secondly, composting, based on UNFCCC (2014) data for Annex I countries, Gupta et al. (1998) for developing countries and Sharholy et al. (2008) for India.

Other historical statistics: Indirect N_2O emissions from atmospheric deposition of nitrogen of NO_x and NH_3 emissions from non-agricultural sources, mainly fossil fuel combustion, are estimated using nitrogen in NO_x and NH_3 emissions from these sources as activity data, based on EDGAR v4.3.2 data for these gases. The same emission factor from IPCC (2006) is used for indirect N_2O from atmospheric deposition of nitrogen from NH_3 and NO_x emissions, as for agricultural emissions. Fossil fuel fires include the Kuwait oil and gas fires with the amount of fuel burnt evaluated by Husain (1994) and the underground coal mine fires evaluated by Van Dijk et al. (2009), mainly for China and India.

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[10] These chemicals are adipic acid, ammonia, acetic acid, acrylonitrile, acetone, acrylic polymers, acetates, acetaldehyde, butadiene, benzene (benzol), butanol, chlorine (Cl2), ethene (ethylene), ethene glycol, ethene oxide, formaldehyde (methanal), maleic anhydride, methanol, polyethene LD + HD (total polyethylene), phenol, polypropene, propene, polystyrene (total), phthalic anhydride, poly Vinyl Chloride (PVC), rubber, total (SBR + synthetic), styrene, toluene, urea, vinyl chloride, xylenes.

2.4 Temporal profiles for the monthly distribution of the annual emissions

The legal reporting obligations under UNFCCC require time-series of annual inventories, in line with the output of most national statistics infrastructures with accurate, annual accounting. In addition, for the atmospheric models, a higher temporal resolution is essential.

Table S4a summarizes the sector specific monthly profiles applied to the aggregated sectors for each GHG in the northern hemisphere. The largest variation is found in the temporal profiles from Asman (1992) for the agricultural sector (see Fig. S2 in the Supplement). A smaller modulation in emissions from residential heating is seen in the temporal profiles of Friedrich and Reis (2004), based on the GENEMIS model, while the modulation of the power generation sector is from Veldt (1992) based on the LOTOS database of Builtjes (1992). Covering regions from all over the world, a reverse profile is applied to the southern hemisphere, reflecting the opposite seasonality. No seasonal pattern is used for the equatorial region, defined within the range of [30°S, 30°N] latitude. For the monthly distribution of shipping emissions, the profile of Wang et al. (2008) is applied while aviation is distributed with the temporal profile of the AERO2K project of Eyers et al. (2004). For more refined time profiles (hourly) and in-depth analysis of the temporal distribution we refer to Thiruchitampalam (2012) and Andres et al. (2011).

2.5 Proxy data for the spatial distribution of the country total emissions

For visualisation and as an input to global chemistry transport and climate models, the EDGAR v4.3.2 database distributes anthropogenic pollutant emissions over a uniform, global 0.1°x0.1° grid defined with lower left coordinates. In emission inventories the emissions can be emitted either from a single point source or distributed over a linear source (e.g. roads) or over an areal source (e.g. agricultural fields), depending on the source sector or subsector. The line and area sources are distributed over the grid cells with the proxy data covering the globe entirely or partially, whereas the point sources are allocated to individual grid cells and reported as the area average of the sum of the point sources for that grid cell.

The proxy datasets that are used to grid different sector-specific sources are given in Table S4b of the Supplement. A detailed description is available in the EDGAR gridding manual (Janssens-Maenhout et al., 2013). A key proxy dataset is the gridded world population provided by the Center for International Earth Science Information Network (CIESIN) of the Columbia University (updated in 2011) for the years 1990, 1995, 2000, 2005, 2010 and projected to 2015. In-house proxy datasets are developed by dividing the total population into rural and urban. These data are applied in order to exactly match the country area and population and take into account the fraction of country data in cells with an intersection of the country's borders.

For the agricultural emission sources with diffuse areal distribution, agricultural land use and soil type maps, such as grassland and cropland cover datasets, rice cultivation area and animal density maps from FAO Geonetwork (2011, 2014) and Monfreda et al. (2008) are used. Coastal fishing activities are distributed on the artisanal fishing map of Halpern et al. (2015).

Industrial activities (power plants, oil refineries, mines) are mainly located at the plant location coordinates on the point source grid-maps. Power plant emissions have been distributed according to the CARMAv3.0 (2012) point source distribution making use of the CARMAv3.0 intensity parameter and differentiating three fuel types (coal, gas and oil). CARMA's point sources with low intensity are used to allocate emissions from auto-producing power or heat plants. A specific proxy was developed for the non-metallic minerals production (mainly cement and lime) for the world leading producers of cement (i.e. Brazil, USA, China and India) based on the plant locations and annual throughput of the facility listed by the CEC (2014) for China, Canada and Mexico, EPRTRv4.2 for Europe and USGS (2016) and Industry about (2016) for the rest of the world. Because of the incompleteness of the list of cement factories (in particular also those with smaller throughput), the country total is not fully distributed over the single reported point sources. Instead annual emission estimates per facility were applied. The difference between the total of the facility emissions and the country total of the given sector is distributed using of urban population data. Gas flaring activities are distributed on NOAA's night-time light data (Elvidge et al., 2009) for those areas of Central America, Nigeria and Western Africa, the North Sea region, Middle East and Russia with strong gas flaring activities. For the major coal producers (i.e., China, USA and Southern Africa) the coordinates of coal mines from the World coal association (2016) are used to distribute emissions from underground and surface coal mines, also distinguishing between hard and brown coal. Coal mine locations for China have been updated and extended with the data of Liu et al. (2015).

Line sources are exclusively used to describe emissions from the transport sector. Different proxy data layers for three road types worldwide (highways, primary and secondary, residential and commercial roads) obtained from the OpenStreetMap of Geofabrik (2015) are used with different weighting factors for the emission distribution, depending on the type of vehicles circulating on the different types of roads. Similar data from OpenRailwayMap are used for railways. For inland waterways the maritime traffic lines (for ships and ferries) are composed from the navigable parts of rivers and lakes, using the InlandWaterwaysMap of the US Department of Transport (2015) for the USA, the UNECE Waterway network (2015) for Europe[11] and the hydrology map of Lehner et al. (2011) for the rest of the world. Wang et al. (2008) is used for international shipping, updated for the Mediterranean, Black and Baltic Sea with Long Range Identification and Tracking data from the European Maritime Safety Agency, as described in Trombetti et al. (2017). The spatial proxy for the aviation sector is derived from International Civil Aviation Organization (ICAO, 2015) flight information and is specified at three different heights: takeoff/landing, climb-out/descending and cruise (see Fig. S1 in the Supplementary). ICAO (2015) specifies a typical flight pattern with landing/take-off cycle within few km of the airport, followed by climb-out/descending phase up to the first and the last 100km of a flight and finally the remaining part from km 101 to the last 101 km as the cruise phase. Input data regarding airports and routes used in this approach are taken from "Airline Route Mapper". Civil supersonic aviation using the Franco-British Concorde between 1976 and 2003 and the Russian Tupolev TU-144 between 1970 and 1983 are also included.

An analysis of the spatial representativeness of the proxy data and the spatial correlation of the data falls outside the scope of this paper. However, it should be noted that although point sources for a given country do not correlate with neighbouring grid cells, they are jointly constrained by the country total for that sector. Line sources are correlated one-dimensionally along the lines within the length of the total network in a country. For

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[11] The domain is defined from [30°N, 82°N] and from [30°W, 90°E]

diffusive sources, which are e.g. gridded with population data, we recommend an isotropic correlation length that is representative of the size of a country. This is of the order of 220 km for the EU-28, but for larger countries the correlation length can be almost double (up to 390 km). For more detailed considerations of uncertainty grid-maps we refer to Andres et al. (2016).

3. Resulting trends

3.1 Global Greenhouse Gases 1970-2012

Figure 3 shows the global trend of GHG emissions in CO_2-equivalent (100 year time horizon), using the GWP-100 values recommended for Annex I National Inventory Reports to UNFCCC and assuming carbon-neutrality for CO_2 emissions from short cycle C (released by combusting biofuels, agricultural waste burning or field burning). The GHG total is composed of all sources of CH_4 and N_2O but only CO_2 from long cycle C fossil sources. The estimated global total GHG in 2010 of 44.7 Pg CO_{2eq} is 0.7% lower than the estimates for the 2010 global total (without LULUCF) in the UNEP (2012, 2015) Emission Gap reports.

In the latest UNFCCC revision of the reporting guidelines adopted by COP (2014), it was decided to use the global warming potential coefficients (GWP-100) from AR4 (IPCC, 2007) with 25 for CH_4 and 298 for N_2O, for the reporting from 2015 onwards. This gives an increased weighting to CH_4 compared to the previous UNFCCC reporting using GWP-100 values of SAR[12] (IPCC, 1996). The weight of CH_4 was further increased in AR5 (IPCC, 2014)[13]. The GWP-100 values from AR4 (and AR5) for CH_4 and N_2O increase the share of total CH_4 from 15.6% to 18.1% (and to 20.0%), while the share of total N_2O decreases from 5.5% to 5.1% (and 4.5% in AR5), and the share of fossil CO_2 falls from 78.9% to 76.8% (and 75.6% in AR5).

In the global GHG emissions time-series, the trend is dominated by CO_2 as it has the largest share and the largest increase. In the 70s N_2O increased at the same rate as CO_2 (2.6%/yr), while CH_4 was half as fast. In the 80s and 90s, N_2O and CH_4 increases were very small, while CO_2 continued albeit at a slower rate (1.6%/yr). In the last decade 2002-2012 CO_2 and CH_4 growth rates increased with respectively 3.2%/yr and 2.0%/yr. While over the four decades (1970-2012) the global total GHG increased in line with global population (91% versus 88%), the inter-annual and regional emission variations do not always reflect the rates in population increase but are instead better explained by the global fuel markets and economy, with the 1973 and 1979 oil crises, the dissolution of the Soviet Union (1989-1991), the growth of the Chinese economy, after they joined the World Trade Organisation in 2002 and the 2008 global financial crisis.

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[12] In SAR (IPCC, 1996b): GWP-100 of CH_4 = 21 and GWP-100 of N_2O = 310

[13] In AR5 (IPCC, 2014): GWP-100 of CH_4 = 28 and GWP-100 of N_2O = 265

3.2 Regional greenhouse gas trend analysis and uncertainty

There are notable differences in trend and uncertainty in the annual GHG inventories of different countries. For the first climate assessment by the IPCC, the world was divided into the 24 OECD countries[14] of 1990 (hereafter denoted "24OECD90"), the 16 countries with Economies in Transition[15] (mainly the Commonwealth of Independent States) (hereafter denoted "16EIT90") and the developing non-Annex I countries of the UNFCCC. Annex I countries were asked to report their GHG inventories annually. As the 24OECD90 countries were stable economically, we have inferred that, they would already have or be able to build a good statistical infrastructure and thus have the lowest uncertainties in their inventories. The 16EIT90 have experienced greater economic instability, from which we infer that their inventories are more uncertain than those of the 24OECD90, but less uncertain than those from the non-Annex I countries. Exceptions to the country grouping are made for the following new or historic trading nations, China, Russia and India, because of global proliferation of emission-regulated goods, as Crippa et al. (2016b) analysed for air pollution.

We have not done any detailed sector- and country-specific uncertainty analyses. Instead uncertainty trends per country grouping and gas were calculated using the formula (4) and the parameters reported in Table 2, which also identifies a few countries as examples of GHG emissions reporting.

$$\sigma_{GHG} = \frac{\sqrt{(\sigma_{CO2} EM_i(CO_2))^2 + (\sigma_{CH4} EM_i(CH_4))^2 + (\sigma_{N2O} EM_i(N_2O))^2}}{EM_i(CO_2) + 25 EM_i(CH_4) + 298 EM_i(N_2O)} \tag{4}$$

For comparative shares and trends in biofuel or non CO_2 GHG emissions, data on gases and sources are much more uncertain. While Denier van der Gon et al. (2015) indicate that country specific estimates of CO_2 from biofuel burning emissions are particularly difficult to ascertain, Tian et al. (2015) estimate the large uncertainties in CH_4 and N_2O budgets. The uncertainties in these emissions are caused by the scarcity and limited accuracy of the corresponding international activity statistics combined with the use of less representative country-wide emission factors (IPCC, 2006; Olivier, 2002; Olivier et al., 2010).

Using this approach, the uncertainty in the global total anthropogenic CO_2 emissions is estimated to range from -9% to +9% (95% confidence interval). This results from larger uncertainties of about +/-15% for non-Annex I countries, whereas uncertainties of less than +/-5% are obtained for the 24OECD90 countries for the time-series from 1990 (Olivier et al, 2015) reported to UNFCCC. For emissions of CH_4 and N_2O, we estimate uncertainties of 32% and 42%, respectively, for 24OECD90 countries and 57% and 93% for the other countries. These are based on the default uncertainty estimates of IPCC (2006) and in line with Bun et al. (2010). Observation-based verification of European CH_4 and N_2O emissions using inverse modelling (e.g. Bergamaschi et al., 2015; 2017)

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[14] Australia, Austria, Belgium, Canada, Switzerland, Germany, Denmark, Spain, Finland, France, United Kingdom, Greece, Ireland, Iceland, Italy, Japan, Luxembourg, The Netherlands, Norway, New Zealand, Portugal, Sweden, Turkey, USA

[15] Bulgaria, Belarus, Cyprus, Czech Republic, Estonia, Croatia, Hungary, Lithuania, Latvia, Malta, Poland, Romania, Russia, Slovakia, Slovenia, Ukraine

indicates that the relatively low uncertainty estimates for some countries are not consistent with the relatively large uncertainty estimates of others, and for CH_4 a common uncertainty band in the upper range is considered more appropriate.

Figure 4 shows the GHG trends for the major regions: 24OECD90 (split into USA, EU15 and the rest), 16EIT90 (with Russia and EU13 and the rest) and non-Annex I (for which China, India and Brazil are shown separately). The EU15 have a negative trend (-0.3%/yr in average over 1970-2012) with decreasing uncertainty. This decrease is composed of negative trends in CH_4 of -0.8%/yr (in average over 1970-2012), N_2O of -0.9%/yr and CO_2 of -0.2%/yr. The latter is due to decreases in the residential and manufacturing industry (-25% and -55%) only being partly compensated for by energy production and road transport increases (39% and 142%) over the 42 years. The GHG decrease in EU15 (and even EU28) in the last decade is primarily based on the decrease in CH_4. The CH_4 decrease seen in EDGAR v4.3.2 is primarily due to the estimated reduction in landfill gas (with 43% over the period 1995-2012), and in addition to the fact that Germany and UK considerably reduced the coal mining activities (and corresponding fugitive emissions), both with 96%.

For the USA the decrease in CH_4 and N_2O emissions of -0.2%/yr and -0.1% respectively, is partly compensated for by the increase in CO_2 (0.3%/yr). The US CO_2 emissions trend is underpinned by increases in energy production (+140% from 1970-2005, followed by only a recent decrease of -16% for 2006-2012) and road transport (+84%), both partly offset by reductions in the residential and manufacturing industry (-32% and -62%). The decrease in CH_4 emissions in the USA is due to the reduction in the landfill emissions (-26%) in EDGAR v4.3.2 but, unlike in the EU15, there is not a reduction in emissions from fossil fuel production. Even though coal mining activities have declined in USA, this is more than compensated for by increasing emissions from shale oil and gas exploration, in particular since 2007. The remaining 24OECD90 countries that report as Annex I countries to UNFCCC have a total increase in GHG emissions of 1.2%/yr. Their average CO_2 emissions increase of 1.4%/yr is higher than either the EU15 or the USA, and is driven by emissions from Turkey (5.0%/yr) and Australia (2.4%/yr) rather than Japan or Canada (which both show smaller increases of 1.1%/yr). Energy production increased with a 12-fold in Turkey and 4-fold in Australia. Unlike the USA and EU15, the remaining 24OECD90 countries also show increases in the CH_4 and N_2O emissions of 0.2%/yr and 0.8%/yr over the period 1970-2012. CH_4 emissions increased in particular in Turkey, due to a 16-fold increase of the landfill CH_4 and a 1.6 times increase of the enteric fermentation from cattle. N_2O emissions increased most in Australia, Canada and Turkey, due to increased N-fertiliser use on agricultural soils (respectively, 10, 6 and 5 times more in 2012 compared to 1970). In addition, Turkey produced considerable amount of adipic acid in 2012, which is estimated[16] to contribute to 33% of its total, although all other 24OECD90 countries have introduced N_2O abatement measures since 1998[17], reducing these emissions by at least 90%.

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[16] The review report of Turkish UNFCCC inventory recommended indicating that it is “included elsewhere” instead of “not occurring”.

[17] USA since 1990 and Italy since 2006

Russia, the East EU13 and the remaining 16EIT90 countries show different GHG trends with decreases in the early nineties, which can be explained by the CO_2 emissions decreases due to the economic recession after the Soviet breakup. Only Russia preceded this CO_2 (CH_4) drop of -6.1%/yr (-4.8%/yr) in 1991-1993 by a relative large increase in the eighties of 2.0%/yr (1.5%/yr) resulting in a total 0.7%/yr (and 1.0%/yr) increase over the period 1970-2012. The CO_2 trend of Russia is strongly driven by emissions from energy production (in particular of public cogeneration gas plants). The CH_4 trend in EDGAR v4.3.2 shows for Russia an increase from 1970-1989, followed by a decrease during 1989-1998, and increases from 1989 onwards. This trend is mainly determined by the fossil fuel production sector, with a 3.7-fold increase of the natural gas production activity in 1970-1991, which then stabilises at -0.1%/yr. Fugitive emissions from the gas transmission pipelines (accounting about 20% of total gas emissions) and from the gas distribution network (accounting about 30%) increase in proportion with the expansion of the pipeline network with 277% and 342% respectively between 1970-1991, followed by much smaller increases of 13% and 20% respectively between 1992-2012. In 2012 venting from oil and gas exploration facilities contributes 1.25 times more than the total gas transmission and distribution emissions, with even much higher emission rates in the 70s. This is discussed later in section 3.3.2 in comparison to other emissions databases. Other changes in the CH_4 trend of Russia estimated by EDGAR v4.3.2 are the reduction in enteric fermentation emissions due to a halving of the cattle between 1990 and 2000 and a 1.5-fold CH_4 emission increase from landfills between 2000 and 2012. For EU13, CO_2 and CH_4 emissions decrease by -0.4%/yr and -0.9%/yr respectively. The fall in CO_2 from 1988 to 1994 in the EU13 was caused by falls in emissions from public cogeneration coal plants (-58%), the residential sector (-39%) and manufacturing industry (-49%). The decrease in the CH_4 emissions from 1988 to 2000 is due to a 43% reduction in emissions from cattle and a 67% reduction in emissions from hard coal mining. For N_2O a decrease of -0.6%/yr over the period 1970-2012 is estimated in total for 16EIT90 (incl. Russia).

Together the non-Annex I countries show an increasing GHG emissions trend, mainly driven by the emerging economies among the developing countries. China overtook the USA as the single largest emitting country around 2003 and since then emissions have increased on average 7.8%/yr in the period 2003-2011, although in 2012 this slowed down to 2.5%/yr in 2012. India has also increased its emission rate since 2009 (to an average of 4.6%/yr for the period 2009-2012) and Brazil could follow this example in the near future (being at 3.4%/yr for the same period). Even though the remaining 180 non-Annex I countries are since 2011 together emitting less than China, they are important in determining the potential upper range for global totals due to their steady increase (on average 2.7%/yr) and greater uncertainty in the true levels of their emissions. Analysing China, India and Brazil in more detail, the similarities between China and India are remarkable. Over the period 1970-2012 both countries dramatically increased CO_2 emissions from public electricity generation by coal power plants (with factor 35 for China and 31 for India), moderately increased CH_4 (for China predominantly due to a 6-fold increase in emissions from coal production and for India due to the 1.8 times increase in emissions from enteric fermentation, in both cases compensated partially by a reduction in emissions from rice cultivation of 37% and 26% respectively) and 11 and 12 times increases in N_2O emissions from use of N-fertilisers respectively. Brazil shows some similarity with India regarding the increase in cattle (and respective CH_4 from enteric fermentation and N_2O from pasture) with factor 2.9 for Brazil and 1.8 (of cattle and buffaloes) for India. CO_2 emissions Brazil increased less fast from the power production sector (factor 7) but faster from the manufacturing industry (factor 4.1) compared to India. CO_2 emissions from manufacturing increased over the 42 years with a factor 3.8 in India and a factor 17.8 in China.

Figure 5 focuses on a comparison with reported UNFCCC (2014, 2016) emissions for the top four emitting countries and regions (China, USA, EU28, Russia). There is a very good agreement between the UNFCCC reported values and the EDGAR v4.3.2 estimates for the EU28, whereas for USA and Russia the EDGAR v4.3.2 estimates are lower than those reported by UNFCCC (2016). For the USA this is explained by lower N_2O emissions in EDGAR v4.3.2, although N_2O emissions reported by USA to UNFCCC (2014, 2016) are within the large uncertainty range for the EDGAR v4.3.2 estimates. For Russia CH_4 emissions reported to UNFCCC (2016) are 37% higher than those estimated by EDGAR v4.3.2, although this is also within the uncertainty range. The largest difference is found in the estimation of gas pipeline transmission emissions, which are 4 times higher in the UNFCCC inventory of Russia than in EDGAR v4.3.2. The relatively low emission factor for gas pipelines, used by EDGAR, is in line with the recommendations of Lelieveld et al. (2005). For China, a very good agreement between the EDGAR v4.3.2 estimate and the UNFCCC (2004, 2012, 2017) reported values is obtained, taking into account the importance of the coal statistics abstract revision. In order to evaluate the latter effect, two emission inventory time series are calculated by EDGAR, with and without coal statistics abstract revision. It is evident that the previous estimates of the UNFCCC inventory in 2005 and 1994 would need to be revised in order to evaluate the emissions change from 2005 to 2012. This is discussed later in section 3.3.1 in comparison to other emissions databases. Even if relative uncertainty in EDGAR estimates for China could be reduced, it is evident that the size of the Chinese inventory has large impact on the global absolute uncertainty.

3.3 Inter-comparison of EDGAR v4.3.2 with other global datasets

3.3.1 Global CO_2 emissions

Table 3 summarises the main features of eight global CO_2 datasets (EDGAR v4.3.2; GCP, Le Quéré et al., 2016; PKU-FUEL, Wang et al., 2013; ODIAC, Oda and Maksyutov, 2011; CDIAC, Andres et al., 2014; EIA, 2014; IEA, 2014; BP, 2016) in temporal and spatial characteristics, sources break-down, methodology and CO_2 totals for major source categories in 2010 (which, for ODIAC and PKU-FUEL, was approximated by the latest available year, 2007). Regardless of the substantially different levels of detail for the fuel use calculations, the global totals are relatively similar. It should be noted that differences for individual countries can be significantly larger (Marland et al., 2009; Olivier et al., 2014).

At global level the differences in CO_2 emissions between IEA (2014) and EDGAR v4.3.2 are around 4%, which can be explained largely by the difference in overall emission factors used (differences due to different default values for the emission factors and carbon oxidation factors in the 1996 and 2006 IPCC Guidelines for Greenhouse gas Inventories (IPCC, 1996, 2006). The latter changes results in 2%, 1% and 0.5% higher CO_2 emissions from respectively coal, oil and gas combustion, and increases overall fossil fuel emissions by about 1.3%. In addition, the latest IEA statistics for recent years show more updated values for fuel consumption than for years further in the past. Marland et al. (1999) compared for the first time the EDGAR and CDIAC datasets. Andres et al. (2012) followed this further up with a more detailed analysed of the differences between the global CO_2 datasets available in 2012, including the earlier version of EDGAR v4.2 (EC-JRC/PBL, 2011), IEA (2012), CDIAC (2012) and EIA (2012). One of the remaining differences is that the flaring in EDGAR v4.3.2 is twice as high as in CDIAC and EIA, which is explained by the different estimation method for the activity data (reported energy statistics in CDIAC and EIA versus satellite data in EDGAR). Although the different EDGAR datasets deviate less than 0.5% for Annex I countries, this deviation becomes 3.4% for non-Annex I countries (see Figure S3 in the Supplementary).

Fig. 6a examines most important non-combustion related CO_2 emissions comparing estimates of EDGAR v4.3.2 with those of Le Quéré et al. (2016) and Xi et al. (2016) for process emissions of the non-metallic sector (cement, lime, dolomite limestone, ceramics and glass production). CO_2 from cement production in EDGAR v4.3.2 is 13% (19%) lower than in Xi et al. (2016) (based on CDIAC) because of the correction for the fraction of clinker in the cement produced. Fig. 6b zooms in regionally on China and compares EDGAR v4.3.2 estimates per sector with those of Guan et al. (2012) and Liu et al. (2015). Guan et al. (2012) indicated the 1.4Gton CO_2 gap in the national total compared to the sum of the provincial statistics and proposed 9.1 Gton CO_2 in 2010. The EDGAR v.4.3.2 estimate of 8.8 ton CO_2 for 2010 differ only by -3%, which is composed of a difference of -19% for the fossil fuel combustion emissions and of +27% for the process emissions. In 2015 China revised its coal statistics and taking into account the lower energy content in the coal, the energy consumption was considerably decreased (for coal power plants with -12%). This was followed by the analysis of Liu et al. (2015), measuring the energy content of coal from over 4200 Chinese mines. In EDGAR v4.3.2 the change in CO_2 emissions for 1990-2012 corresponding to the revision of the IEA (2014) China data to IEA (2016) data resulted in an emission reduction from power generation of –8% but on the CO_2 total of only -2% for 2010. However, while the revision includes a decrease of the 2010-2012 values, it yields an increase for the 1990-2009 values of about +3% for 2005 and 1994, which should be accounted for when comparing the UNFCCC 2005 and 1994 inventories with the 2012 one. Although Liu et al. (2015) reported 14% lower emissions compared to EDGAR, this is effectively only 6% when correcting for the flaring, coke production, chemicals production and limestone which were not accounted for in their study. This 6% difference is well within the uncertainty range for China's CO_2 emissions and can be attributed to the non-oxidation fraction of 8% that was used in their study for coal burning, while the EDGAR emissions assume a non-oxidation fraction of 0%, as recommended by IPCC (2006) in absence of representative national data. Even though the average carbon content per tonne domestic coal is much lower than the IPCC default values (because of the low quality and high ash content of Chinese coal), the average carbon content per unit of energy measured for Chinese coal differs only 2% from the IPCC default value for bituminous coal (IPCC, 2006). Moreover, the average net calorific value measured for Chinese coal is only 3% lower than the value used for bituminous Chinese coal in EDGAR.

3.3.2 Global CH_4 emissions

Table 4 compares the CH_4 global estimates of EDGAR v4.3.2 with four other global datasets (the bottom-up inventories of US EPA, 2012 and GAINS Eclipse v5 of Höglund-Isaksson et al., 2012); and the global budgets of Kirschke et al., 2013 and Saunois et al., 2016). Even though the global total CH_4 emissions for the bottom-up inventories vary less than 4%, global annual emissions from the agricultural and fossil fuel production sectors vary with +/-22% and +/-17%, respectively. The top-down inventory estimates are 16%~29% larger than the bottom-up ones.

Figure 7a illustrates the origin of the large variations in the estimated fugitive emissions of oil and gas production (including extraction, transmission and distribution). Large uncertainties in CH_4 from venting and flaring at oil & gas extraction facilities have been reported by e.g. Lyon et al. (2015) or Peischl et al. (2015). The CH_4 venting of oil and gas extraction facilities is in particular during the time of the Soviet Union is now believed than previously thought (e.g. in EDGAR v4.2 or US EPA), after Höglund-Isaksson (2017) used ethane-methane ratios as an indicator. Additionally gas distribution is a relative large source of uncertainty, in particular in countries with old gas distribution city networks using steel pipes now distributing dry rather than wet gas, with potentially more leakages. Based on IPCC (2006), EMEP/EEA (2009, 2013) and Marcogaz (2013), the emission factors for steel pipes and grey cast iron pipelines therefore vary in the range of 0.1~3 ton/km/yr and 1~7 ton/km/yr, respectively, depending on the country. Since EDGAR estimates emission factors as a function of pipe length with the pipe material as a parameter, any dependence on the composition of the transported gas is accounted for by country-specific variations. PVC pipelines are only assumed to emit between 0.05~0.3 ton/km/yr but for polyethylene pipelines a higher leakage rate of 0.15~2 ton/km/yr is assumed. The high CH_4 emissions during the natural gas transmission in the Russian reporting to UNFCCC (2016) might also account for all or part of accidental CH_4 releases, which are not negligible according to Höglund-Isaksson (2017). These are not included in the EDGAR datasets.

China is currently also the largest source of CH_4 emissions because it has become the largest coal producer and it is a major rice cultivator. While the fugitive CH_4 emissions from coal production in China are increasing, emissions from rice cultivation are decreasing, as shown in Fig. 7b. The emission factor CH_4/ha/yr for irrigated rice fields has been reduced in China from 1970 to 2000 with 1/3 by changing farming practices, as reported by Li et al. (2002), resulting in 0.47 kg CH_4/ha/yr for the last decade. A comparison with Peng et al. (2016) illustrates the large uncertainty in the emission factor (which is twice as high in EDGAR v4.3.2). Also for the coal mining the CH_4 emission factor for China is higher than in Peng et al. (2016), but only 9%. EDGAR v4.3.2 revised emission factors for coal mining with local data from Peng et al. (2016), weighted by coal mine activity per province. These emission factors are at the lower end of IPCC (2006) recommendations and yield EDGAR v4.3.2 estimates of 17.2Tg in 2008 and 21.2Tg in 2012, which are comparable to the estimates of Peng et al. (2016).

Total CH_4 emissions in EDGAR v4.3.2 in 2005 are 2% (3%) lower than in the v4.2 (4.1) version, which is in line with the findings of the global inverse modelling studies of Monteil et al. (2011), Bergamaschi et al. (2013, 2015, 2017), Ganesan et al. (2015), Kort et al. (2008), Miller et al. (2013). Total emissions have not changed significantly for either EU28 or the USA, but there are changes in the patterns of emissions: the -2.5% (-0.2%) change in the EU28 estimates of v4.3.2 compared to those of v4.2 (v4.1) is still within the range of the inverse model simulations of Bergamaschi et al. (2017), while the -4.7% (-3.4%) change in USA in EDGAR v4.3.2 compared to v4.2(v4.1) are not in line with the suggested +50~70% higher anthropogenic emissions based on the inverse modelling study of Miller et al. (2013). The latter might be explained at the emissions side by delayed reporting of statistics on fracking for shale gas and oil and the not well characterised and highly uncertain emission factors as indicated by US EPA (2015) and at the modelling side by large uncertainties of inverse models and the potential contribution of natural sources. For China the EDGAR v4.3.2 estimate for fugitive emissions from coal mining yields a 38% lower CH_4 emissions total in 2008, which is in line with Saunois et al.

(2016), Brandt et al., (2014) and Kirschke et al. (2013), suggesting lower CH_4 emissions in particular in northern China where coal mining takes place.

3.3.3 Global N_2O emissions

The global budget of N_2O is less well studied in scientific literature than the global budgets of CO_2 and CH_4. Moreover the bottom-up estimate of EDGAR v4.3.2 for 2005 compares to the estimated total of US EPA (2014) within 29% (see Table 5), but with differences between the different source categories. A comparison at European level shows less variation: only 13% for the total, and 17% respectively 24% for the agricultural and non-agricultural sectors.

Although in EDGAR v4.3.2 the agricultural sector is contributing most to the anthropogenic direct and indirect N_2O emissions, the production of chemicals, such as nitric acid, glyoxal, caprolactam and adipic acid production, and its use as anaesthesia or for aerosol spray cans also plays an important role. In 1970 the chemicals sector contributed 20% to the total, but this has been significantly reduced to less than 8% because of technological developments. Figure 8 shows the impact of technological developments from old plants to higher pressure plants or plants with non-selective catalytic reduction, reducing the N_2O emissions by factors of 2 and 10, respectively. The N_2O emission trends of nitric acid plants of v4.3.2 are in line with US EPA (2014) estimations for adipic and nitric acid plant facilities.

4. Resulting grid-maps

The previous section (Fig. 5) suggested that the absolute uncertainty of the global inventory is largely determined by the quality of the inventories of the largest emitting countries. The heterogeneity of country sizes does not support an equilibrated evaluation of global emissions at country level. Instead bottom-up inventories could be constructed by accounting for each facility or local human activity, which emits more than a threshold quantity (e.g. 1Mton CO_{2eq}/yr) A point-source database, such as the European Pollutant Release and Transfer Register (EPRTR[18]), allows a more homogeneous input for an inventory compiled under such a facility-based approach. The European study of Theloke et al. (2011), which aimed to complement EPRTR point sources with information on diffusive sources per country that together match national totals, revealed large inconsistencies, which prevented closing the two approaches in a satisfying way. To bridge emissions information at country level with the facility-based one, it is needed to grid the national emissions and distribute the national totals to the respective (sector-specific) point sources.

In this section, the gridded EDGAR datasets at 0.1°x0.1° are further screened to identify hot spots and to check for anomalies. An overview of the region-specific totals and their sector-specific composition for the year 2012 is given in Figs. 9, 12 and 15 for the different substances. The sector-specific country totals are provided in the overview Table 6a per region and 6b per sector for 2012.

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[18] Available under prtr.ec.europa.eu

4.1 CO_2 emissions and urban hot spots

The 2012 grid-map of CO_2 emissions from both long-cycle and short-cycle carbon in Fig. 9 with the relative sectoral breakdown for selected world regions (Europe, North America, Latin America, Africa, Middle East, Oceania, Russia and China) clearly shows the fossil fuel combustion activities, representing 90.6% of the total CO_2 emissions. In this section we include for completeness biofuel emissions, which were omitted from the comparisons with UNFCCC reporting, because UNFCCC assumes carbon neutrality for all agricultural and biofuel CO_2 emissions in a country for any individual year. In the 24OECD90 countries 75.2% of CO_2 emissions are produced by the power, road transport and residential sectors, while these sectors represent only 60.9% in non-Annex I countries. The share of the industrial combustion and production sectors (mining/manufacturing) of non-Annex I countries reaches 36.8%. The CO_2 shares of the fuel combustion in the power generation, road transport, buildings and manufacturing sectors vary for the different regions from 16~50%, 5~27%, 6~39% and 9~22% of total emissions (see Table 6a and 6b) respectively. Interestingly, agricultural waste burning[19] represents 10% of CO_2 emissions in Latin America (mainly due to sugarcane crop residues burning) and 22% of CO_2 emissions in Africa derives from the transformation industry (charcoal production using as input primary solid biomass). Industrial emissions are distributed at the point-source locations of the power/heat plants or industrial facilities (e.g. cement factories) using the capacity of the plants or facilities as a weighting factor.

In the grid-maps hotspots are particularly visible over cities, of which the top 4 are emitting 2.75% of the global total[20] and coincide with the cities of Shanghai, Huangshi, Shenyuang and Moscow. In fact, 5% of the 0.1°x0.1° grid cells are emitting more than 5Mton/(0.1°x0.1°)/yr and account for 34.08% of the global total. It is therefore interesting to look at the contribution of the various sectors in megacities, as shown in Fig. 10. Emissions from the road transport sector (Fig 10a) for the 20 selected cities seem to be more important in suburban areas than in the centre of the megacity. For power plants more heterogeneity is found (Fig. 10b) with larger power plants typically located on the periphery of the city in the 24OECD90 countries, while for major cities of the 16EIT90 and non-Annex I countries, several larger power plants are located within the central city areas. The remaining share of CO_2 emissions is mainly from the buildings sectors and the industrial manufacturing emissions.

The evolution over time from 1970 to 2012 shows a different pattern for the residential sector than for the road transport sector. Fig. 11a shows that while the residential sector decreased over these 4 decades in America and Europe, it increased in Asia and Africa. The difference in CO_2 emissions from the road transport sector meanwhile presents in Fig. 11b a more homogeneous picture with increases from 1970 to 2012 in almost all regions.

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[19] Note that the agricultural waste burning is not including the Savannah burning.

[20] At a rate of more than 125 Mton/(0.5° x 0.5°)

4.2 CH_4 emission maps

Because CH_4 is mainly released from fermentation processes (enteric, manure, landfills or rice) or diffusion processes (coal mine leakage or gas distribution losses), the 2012 CH_4 emission grid-map with sector contributions for major world regions (Fig. 12) does not mirror the same human activities as the CO_2 map. The CH_4 shares for enteric fermentation, fossil fuel production & transmission and solid & water waste treatment range from 9~59%, 8~68% and 11~37% of the global total respectively, depending on the region. For 24OECD90 countries enteric fermentation (with 31.1% share), fossil fuel production (28.1%) and landfills (21.4%) are the three dominant sectors, whereas in the 16EIT90 countries, CH_4 emissions are dominated by fossil fuel production (49.4% share). The non-Annex I countries show a similar high share of enteric fermentation and fossil fuel production as the 24OECD90 countries, but rice cultivation and domestic wastewater together give much higher emissions than solid waste disposal. Rice cultivation contributes significantly to the total CH_4 inventory of China (21.5% or 14.2 Tg in 2012), which is almost 11 times the CH_4 emissions of rice cultivation in India (3.8 Tg), despite the larger area for rice fields in India than in China (425 compared to 303 thousand km^2). This is explained by the fact that India typically has one harvest per year from 1/3 rain-fed fields and 2/3 irrigated fields, whereas China has multiple harvests per year from irrigated rice fields. Rain-fed rice fields in India are modelled with a five times lower emission factor than the irrigated fields in China. Figure 13a and 13b show the opposing trends with mainly positive 2012-1970 increments in enteric fermentation (mainly cattle) (a) and mainly negative increments in CH_4 emissions from rice cultivation (b). The CH_4 trend from rice cultivation in Asia is remarkably stable with the exception of Thailand where increased activity is noticed. The remaining non-Annex I countries of Africa and Latin-America show similar high contributions from enteric fermentation (25.8 Tg versus 20.9 Tg respectively in 2012). However, the total CH_4 emissions from the African continent are higher than those of Latin-America because of the 3.5 times larger CH_4 emissions from fossil fuel production (gas and oil production). Interestingly, both continents show significant CH_4 emissions from charcoal production, which compares to 16% (Africa) and 15% (Latin-America) of their gas and oil production emissions of CH_4.

Hot spots of CH_4 are estimated for fossil fuel production, typically at gas & oil production facilities or at coal mines, as shown in Fig. 14. In North America a shift over the period 2005-2012 from coal mining in the North-East (-21%) to gas & oil production in particular in North-Dakota, Montana and Texas (+65%) took place. The USA is nowadays the largest producer of both shale gas and tight oil, which are making up almost half of total US gas and oil production (EIA, 2015). In Europe a much larger decrease of -87% in coal production happened earlier while gas production increased by 30%. Consequently the EU28 needed to rely on oil and gas imports and expanded its transmission and gas distribution network with corresponding increase in CH_4 leakages. Aside of the USA, also the Middle East is a global world player on the oil and gas market, shifting from oil production (with a decrease of 1/3.5 over the period 1976-1985) to gas production (with a 9.3-fold increase from 1985 to 2012), mainly driven by Iran, Saudi Arabia and Qatar. The African countries with the highest CH_4 emissions from fossil fuel production are in decreasing order of importance Algeria and Nigeria (for oil and gas production) and South Africa (for coal mining). Similarly to Nigeria, which showed an approximate doubling of CH_4 emissions from oil (and gas) production over the last 4 decades, Mexico and Venezuela also show similar levels of CH_4 emissions from oil and gas production (increasing with a factor 1.6 over the 4 decades). For gas production, Russia shows the largest CH_4 venting and leakage, overtaking the USA in 1985.

Coal mining has become important for China, which is since 1982 the largest bituminous coal producer in the world, overtaking the USA. Moreover China is also the largest coal importer since 2011 (overtaking Japan), as domestic coal produced in mainly the western and northern inland provinces of China faced a transportation bottleneck, lacking southbound rail lines (Tu, 2012) towards the southern coast that has the highest coal demand. Not only did EDGAR v4.3.2 revise the country-specific coal mining emission factors, but also the spatial distribution was considerably updated with hot spots at the location of the mining activity. For coal mine activities in China (split in brown and hard coal), the coal mine database of Liu et al. (2015) provided over 4200 coal mine locations, which is 10 times more than that available for EDGAR v4.2. For Europe, the closure of mines since the 1990s have been taken into account using EPRTR (2012).

4.3 N_2O emissions including indirect sources

Unlike the CO_2 and CH_4 grid-maps, the gridded N_2O emissions for the year 2012 in Fig. 15 with the share of different sectors for world regions shows a quite uniform global coverage distribution, due to the predominance of soil emissions and indirect emissions (distributed with the N-deposition map of Dentener et al. (2006)), also from the seas surface. Over land, most N_2O is emitted from the agricultural soils (the use of animal manure as fertiliser, the application of N containing fertilisers and cattle in pasture), representing from 35% to 86% of total N_2O emissions depending on the region. Fertilising farmland with pasture or animal waste as fertiliser or crop residues has not increased so much as the use of nitrogen fertilisers. Figure 16 shows the increased use (by the difference 2012-1970) of nitrogen fertiliser, in particular in Asia.

5. Conclusion and outlook

5.1 Strengths and applications of EDGAR v4.3.2

The scientific global emission inventory database EDGAR v4.3.2 provides a consistent comprehensive dataset of anthropogenic emissions of CO_2, CH_4 and N_2O in time series 1970-2012 (with monthly resolution) and spatially disaggregated grid maps with 0.1°x0.1° resolution. An advantage of EDGAR v4.3.2 is that the bottom-up emissions calculation methodology is consistently applied to all countries. The country-specific EDGAR v4.3.2 GHG emissions are available in a similar structure compared to the reported emissions of the Annex I countries to UNFCCC, which generally have a good statistical data infrastructure and regular reporting system. EDGAR v4.3.2 may provide useful information to countries with less strong statistical data infrastructure for their future inventory requirement. In particular the time-series of EDGAR v4.3.2 can complete the emission trends for non-Annex I countries, as illustrated for the case of China, where the coal statistics revision impacts also the 2005 and the 1994 inventory with +3%. EDGAR v4.3.2 demonstrates that inventories can be developed for all countries in a consistent way within the limitations of the quality of the available statistical data in order to contribute to the comprehensive picture needed for the UNFCCC's global stock take of 2023.

For the atmospheric modelling community EDGAR v4.3.2 enables models to use historical emissions to compare their results with in-situ and remote sensing atmospheric observation records. The results of inverse atmospheric models provide an independent evaluation of the nationally collected emission data with regard to their uncertainty and as such support the scientific review and updates of emission inventory methodologies. Although modelling uncertainties remain large, atmospheric models provide observationally constrained top-down input that is independent from the statistics on which the bottom-up inventories are built. Moreover, the impact of updates of recommended tiered emission factors (such as from IPCC (1996; 2006) and due for further refinement in 2019, or the choice to use more region specific emission factors) on the resulting emissions can be assessed at global scale. The update of the EDGAR v4.2 version to v4.3.2 demonstrated e.g. the necessity to take up region-specific emission factors for fugitive coal mining emissions in China, which are considerably lower than the IPCC Tier 1 default values (e.g. Peng et al., 2016; Saunois et al., 2016).

With the 42 year long time-series of EDGAR v4.3.2 we provide an important input to the analysis of global GHG trends. We find an accelerated increase of GHG emissions since the beginning of the 21st century compared to the three decades before, mainly driven by the increase in CO_2 emissions from countries with emerging economies. For the EU-28 the trend is determined by a rather stable share of CO_2 and a smooth but continuously decreasing CH_4 contribution, within an overall fall in total GHG emissions. Even though overall global uncertainty in total emissions, has increased because of the increasing share of GHG emissions from emerging economy countries, on European scale the uncertainty has decreased because of the progress in inventory compilation and the decrease in more uncertain CH_4 emissions.

Overall the EDGAR v4.3.2 database aims at providing useful information for both the scientific and policy communities involved in understanding GHG emissions and budget, e.g. for the compilation of national inventories, the UNFCCC global stock take, analysis of co-benefits between air pollution and GHG emission mitigation strategies, interpretation of satellite data, understanding and reducing of uncertainties.

5.2 Future perspective

EDGAR v4.3.2 also consistently calculates and distributes emission sources not only for all greenhouse gases, but also for air pollutants, representing multi-pollutant sources as single point source with realistic ratios of the different pollutant emission rates. To analyse the co-benefits and trade-offs of integrated approaches towards air quality and climate and energy as well as air quality policies, it is of key importance to report, monitor and verify a complete inventory of greenhouse gases and air pollutants. The ratio of some air pollutants over greenhouse gases (e.g. ratios of $CO:CO_2$) have been shown to be useful input for interpreting the fossil fuel component of the CO_2 satellite data (Berezin et al., 2013), but needs further evaluation of the technology updates in a future study with the air pollutants part of EDGAR v4.3.2 and a description of the necessary extra technological details.

Emissions provided by the EDGAR database cannot be always considered as the best country or region-specific estimate, as the use of a consistent methodology globally can mean the loss of more detailed local knowledge, and consequently they may differ from local estimates provided by national inventories. However, the global and consistent coverage of the EDGAR v4.3.2 grid-maps allows to generate per grid-cell the emission ratios of different gases or the sector-specific shares, as additional information for interpreting satellite retrievals measuring column-averaged dry-air mole fractions of total CO_2 or CH_4.

6. Access to the data

Annual grid-maps for all GHGs and sectors covering the years 1970-2012 are available as txt (expressed in the unit: ton substance per grid cell) and NetCDF (expressed in the unit: kg substance/m2/s) with 0.1°x0.1° spatial resolution, in the map gallery at http://edgar.jrc.ec.europa.eu/overview.php?v=432&SECURE=123 (DOI: https://data.europa.eu/doi/10.2904/JRC_DATASET_EDGAR). In addition, monthly GHG global grid-maps are produced for 2012 and are available per sector and substance. In section 3.1 we describe the main features of the grid-maps focusing on the year 2012, although analogous considerations also pertain to previous years.

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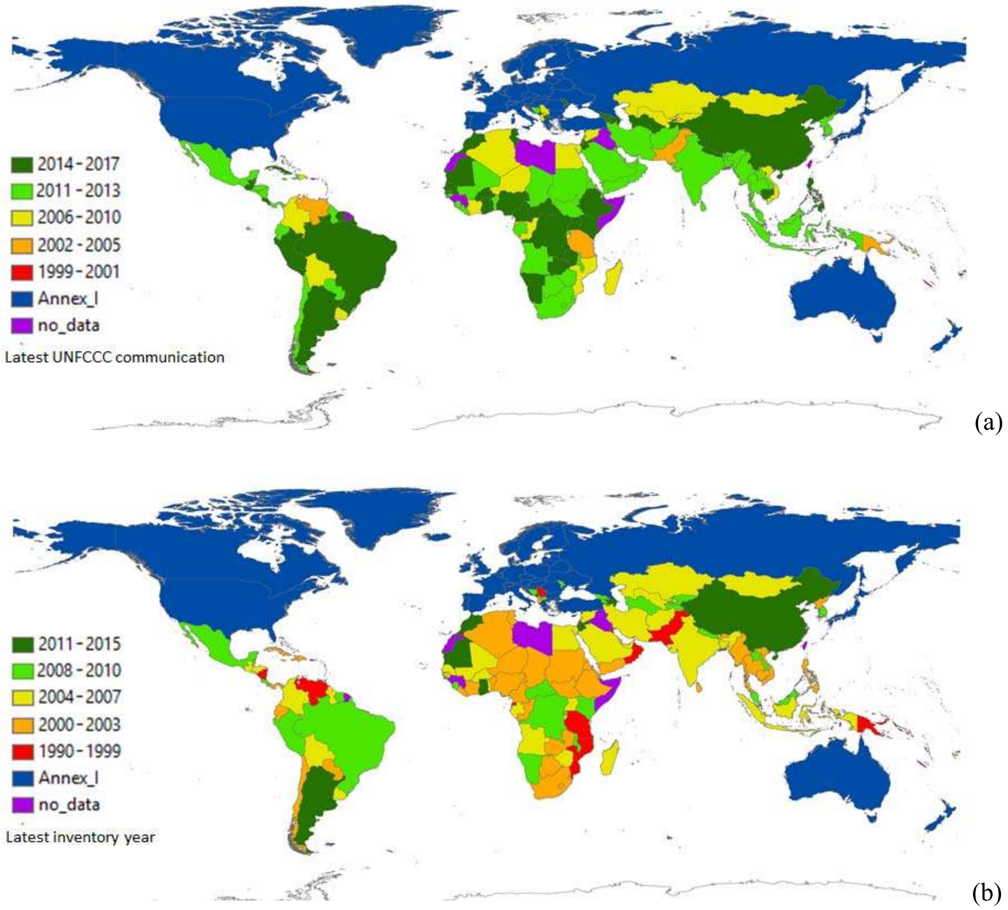


Figure 1: (a) Inventory submission as received at UNFCCC (by January 2017) for all countries: a. year in which the latest national communication to UNFCCC took place, (b.) latest year of the inventory submitted to UNFCCC.

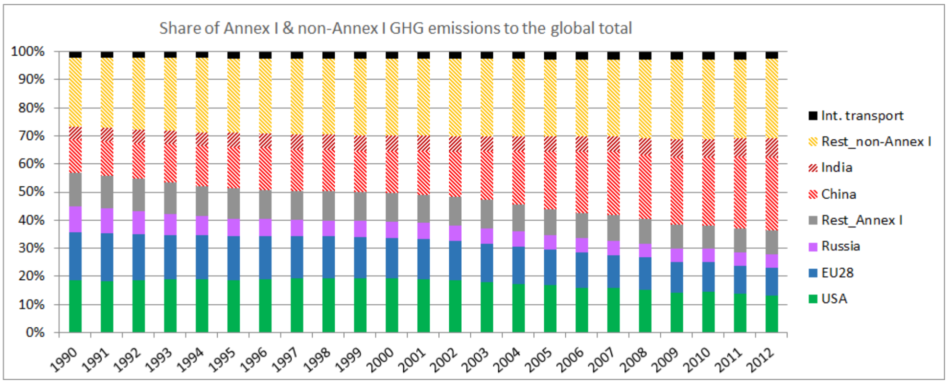
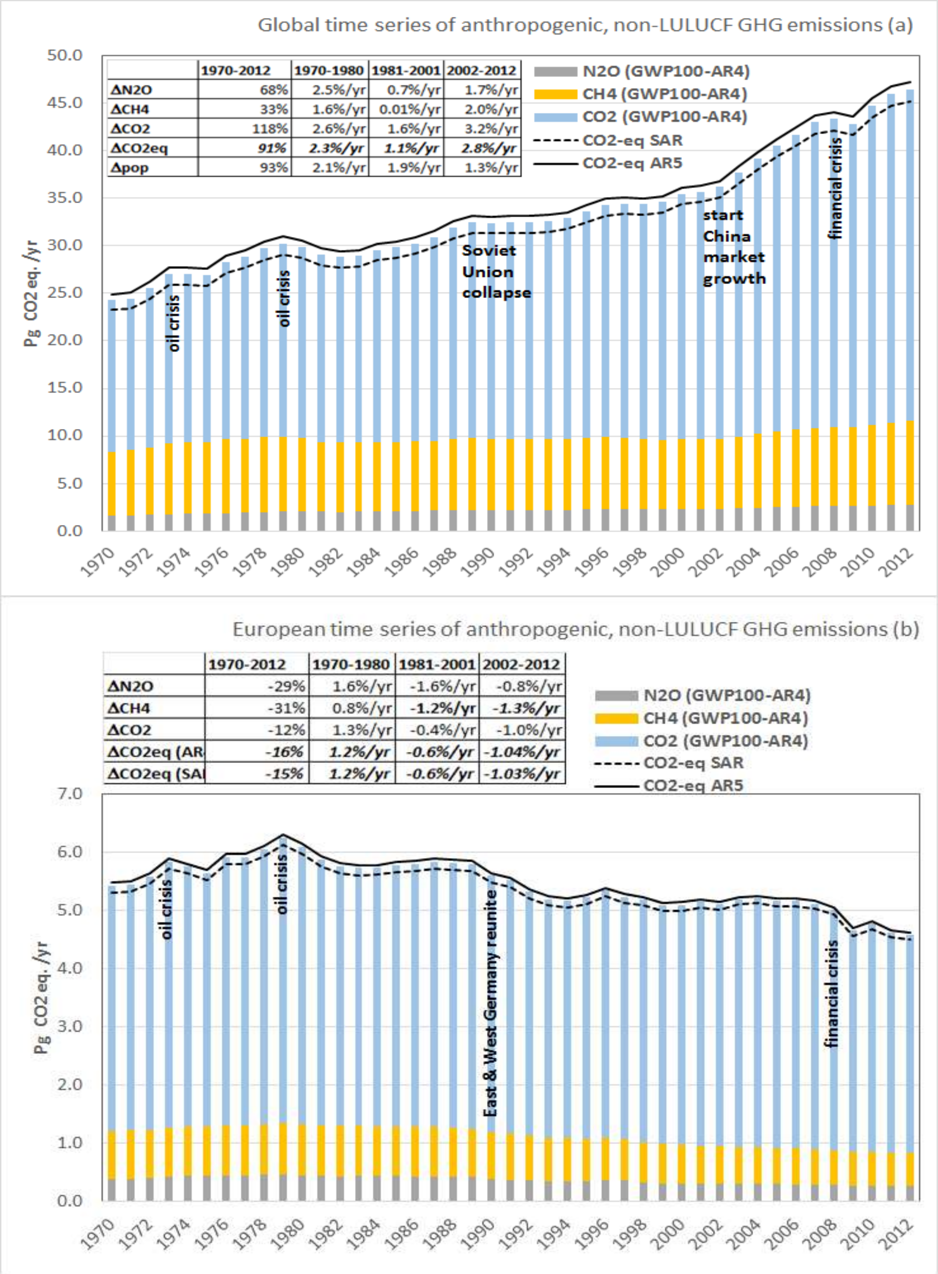


Figure 2: Relative contribution of the Annex I and non-Annex I countries to the global total GHG emissions. The red, brown and orange dashed parts of the stack correspond to the non-Annex I share that increases from about 1/3 in 1990 to almost 2/3 in 2012.

Table 1: Main category with all Source/Sink Categories conform to the IPCC Guidelines (1996). Note that neither large scale biomass burning nor land-use, land-use change and forestry emissions are included, although we do include biofuel combustion and agricultural activities (such as livestock and milk production, crop and rice production, agricultural waste burning, field burning, histosols and liming).

Main category of emission sectors	EDGAR_code	Emission sectors of data delivery	IPCC_1996	IPCC_2006
Energy comprises the production, handling, transmission and combustion of fossil fuels and biofuels and is calculated with energy statistics. For CO2 the short cycle C is split off from the long cycle C, because the short cycle CO2 emitted from the combustion of biofuel is assumed to neutralise the CO2 uptake during the same year the biofuel was grown. Any disequilibrium of this balance needs to be taken up under the Land-Use, Land-use change and forestry sector. As such the long cycle CO2 energy refers to fossil fuel combustion only, the short cycle CO2 energy refers to the biofuel combustion. All other substances include fossil and biofuel combustion.	ENE	Power industry	1A1a	1.A.1.a
	IND	Combustion for manufacturing	1A2	1.A.2
	RCO	Energy for buildings	1A4	1.A.4+ 1.A.5.a+ 1.A.5.b.i+ 1.A.5.b.ii
	REF_TRF	Oil refineries and Transformation industry	1A1b+ 1A1c+ 1A5b1+ 1B1b+ 1B2a5+ 1B2a6+ 1B2b5+ 2C1b	1.A.1.b+ 1.B.2.a.iii.4+ 1.A.1.c+ 1.A.5.b.iii+ 1.B.1.c+ 1.B.2.a.iii.6+ 1.B.2.b.iii.3
	TNR_Aviation_CDS	Aviation climbing&descent	1A3a_CDS	1.A.3.a_CDS
	TNR_Aviation_CRS	Aviation cruise	1A3a_CRS	1.A.3.a_CRS
	TNR_Aviation_LTO	Aviation landing&takeoff	1A3a_LTO	1.A.3.a_LTO
	TNR_Aviation_SPS	Aviation supersonic	1A3a_SPS	1.A.3.a_SPS
	TNR_Other	Railways, pipelines, off-road transport	1A3c+ 1A3e	1.A.3.c+ 1.A.3.e
	TNR_Ship	Shipping	1A3d+ 1C2	1.A.3.d
	TRO	Road transportation	1A3b	1.A.3.b
Fugitive refers mainly to gas flaring and venting during oil and gas production, coalbed methane during underground or surface mining and CH4 distribution losses and evaporation during transmission and mainly distribution. This is based on fuel production statistics, supplemented nightlight observations.	PRO	Fuel exploitation	1B1a+ 1B2a1+ 1B2a2+ 1B2a3+ 1B2a4+ 1B2c	1.B.1.a+ 1.B.2.a.ii+ 1.B.2.a.iii.2+ 1.B.2.a.iii.3+ 1.B.2.b.ii+ 1.B.2.b.iii.2+ 1.B.2.b.iii.4+ 1.B.2.b.iii.5+ 1.C
Industrial Processes refer to non-combustion emissions from either manufacturing of cement, lime, soda ash, carbides, ammonia, methanol, ethylene, methanol, adipic acid, nitric acid, caprolactam, glyoxal and other chemicals, or from production of metals and from the use of soda ash, limestone and dolomite, from production of ferrous and non-ferrous metals and from non-energy use of lubricants and waxes. The emission estimates use the volume of industrial product produced (and traded) from the industry statistics.	CHE	Chemical processes	2B	2.B.1+ 2.B.2+ 2.B.3+ 2.B.4+ 2.B.5+ 2.B.6+ 2.B.8
	FOO_PAP	Food and Paper	2D	2.H
	IRO	Iron and steel production	2C1a+ 2C1c+ 2C1d+ 2C1e+ 2C1f+ 2C2	2.C.1+ 2.C.2
	NEU	Non energy use of fuels	2G	2.D.1+ 2.D.2+ 2.D.4
	NFE	Non-ferrous metals production	2C3+ 2C4+ 2C5	2.C.3+ 2.C.4+ 2.C.5+ 2.C.6+ 2.C.7
	NMM	Non-metallic minerals production	2A	2.A

Solvents and Products use includes CO2 from solvents in paint, degreasing and dry cleaning, chemical products and other product use, as well as use of N2O as anaesthesia and in aerosol spray cans. Estimates are based on a combination of population and solvents statistics.	PRU_SOL	Solvents and products use	3	2.B.9+ 2E+ 2F+ 2G+ 2D3
Agriculture comprises the application of urea and agricultural lime, enteric fermentation, rice cultivation, enteric fermentation, manure management, fertiliser use (synthetic and manure), agricultural waste burning (in field) and is based on agricultural statistics. Large scale biomass burning from Savannah is not included.	AGS	Agricultural soils	4C+ 4D	3.C.2+ 3.C.3+ 3.C.4+ 3.C.7
	AWB	Agricultural waste burning	4F	3.C.1.b
	ENF	Enteric fermentation	4A	3.A.1
	MNM	Manure management	4B	3.A.2
Waste comprises landfills and wastewater management, and waste incineration that is not producing energy (neither generation of electricity nor heat recovery, because these are accounted in the energy sector(non-energy). Estimates are based on a combination of population and solid and liquid waste product statistics.	SWD_INC	Solid waste incineration	6C	4.C
	SWD_LDF	Solid waste landfills	6A+ 6D	4.A+ 4.B
	WWT	Waste water handling	6B	4.D
Other refers to direct emissions from fossil fuel fires (coal fires & the Kuwait oil fires), N2O usage and indirect emissions from atmospheric deposition of NOx and NH3 from non-agricultural sources, for which other historical statistics are consulted.	FFF	Fossil Fuel Fires	7A	5.B
	IDE	Indirect Emissions	7C	5.A
	N2O	Indirect N2O from agriculture	4D3	3.C.5+ 3.C.6

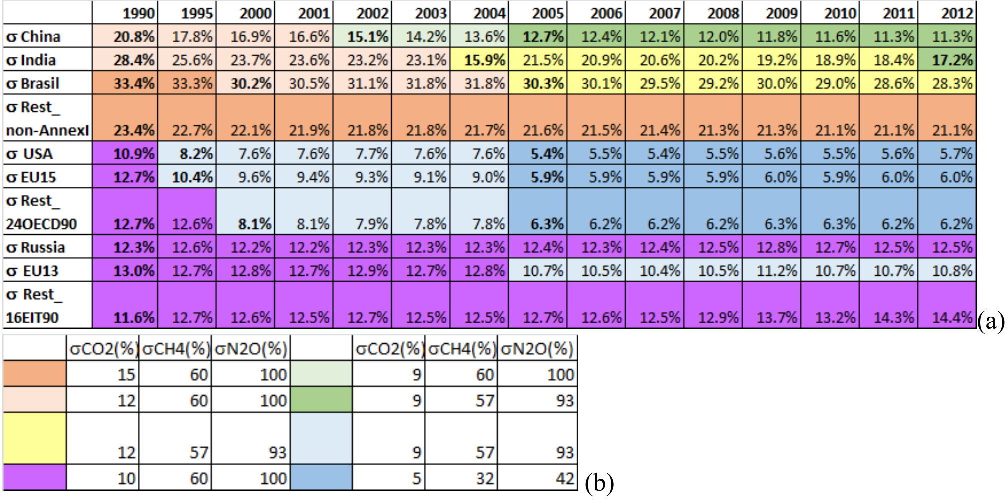


	1970-2012	1970-1980	1981-2001	2002-2012
ΔN2O	68%	2.5%/yr	0.7%/yr	1.7%/yr
ΔCH4	33%	1.6%/yr	0.01%/yr	2.0%/yr
ΔCO2	118%	2.6%/yr	1.6%/yr	3.2%/yr
ΔCO2eq	***91%***	***2.3%/yr***	***1.1%/yr***	***2.8%/yr***
Δpop	93%	2.1%/yr	1.9%/yr	1.3%/yr

	1970-2012	1970-1980	1981-2001	2002-2012
ΔN2O	-29%	1.6%/yr	-1.6%/yr	-0.8%/yr
ΔCH4	-31%	0.8%/yr	**-1.2%/yr**	***-1.3%/yr***
ΔCO2	-12%	1.3%/yr	-0.4%/yr	-1.0%/yr
ΔCO2eq (AR	***-16%***	***1.2%/yr***	***-0.6%/yr***	***-1.04%/yr***
ΔCO2eq (SA	***-15%***	***1.2%/yr***	***-0.6%/yr***	***-1.03%/yr***

Figure 3: (a) Timeseries 1970-2012 of fossil fuel CO_2, CH_4 and N_2O global emissions from human activities excluding the LULUCF sector. The stacked bars use AR4 GWP-100 values whereas the dashed line and full line indicate the total CO_{2eq} of the three gases in the case the SAR and the AR5 GWP-100 values are respectively used.

Table 2: Uncertainty of the GHG inventory for countries and country types (a) with the uncertainties per gas (b)



	1990	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
σ China	**20.8%**	17.8%	16.9%	16.6%	**15.1%**	14.2%	13.6%	**12.7%**	12.4%	12.1%	12.0%	11.8%	11.6%	11.3%	11.3%
σ India	**28.4%**	25.6%	23.7%	23.6%	23.2%	23.1%	**15.9%**	21.5%	20.9%	20.6%	20.2%	19.2%	18.9%	18.4%	**17.2%**
σ Brasil	**33.4%**	33.3%	**30.2%**	30.5%	31.1%	31.8%	31.8%	**30.3%**	30.1%	29.5%	29.2%	30.0%	29.0%	28.6%	28.3%
σ Rest_ non-AnnexI	**23.4%**	22.7%	22.1%	21.9%	21.8%	21.8%	21.7%	21.6%	21.5%	21.4%	21.3%	21.3%	21.1%	21.1%	21.1%
σ USA	**10.9%**	**8.2%**	7.6%	7.6%	7.7%	7.6%	7.6%	**5.4%**	5.5%	5.4%	5.5%	5.6%	5.5%	5.6%	5.7%
σ EU15	**12.7%**	**10.4%**	9.6%	9.4%	9.3%	9.1%	9.0%	**5.9%**	5.9%	5.9%	5.9%	6.0%	5.9%	6.0%	6.0%
σ Rest_ 24OECD90	**12.7%**	12.6%	**8.1%**	8.1%	7.9%	7.8%	7.8%	**6.3%**	6.2%	6.2%	6.2%	6.3%	6.3%	6.2%	6.2%
σ Russia	**12.3%**	12.6%	12.2%	12.2%	12.3%	12.3%	12.3%	12.4%	12.3%	12.4%	12.5%	12.8%	12.7%	12.5%	12.5%
σ EU13	**13.0%**	12.7%	12.8%	12.7%	12.9%	12.7%	12.8%	10.7%	10.5%	10.4%	10.5%	11.2%	10.7%	10.7%	10.8%
σ Rest_ 16EIT90	**11.6%**	12.7%	12.6%	12.5%	12.7%	12.5%	12.5%	12.7%	12.6%	12.5%	12.9%	13.7%	13.2%	14.3%	14.4%

(a)

	σCO2(%)	σCH4(%)	σN2O(%)		σCO2(%)	σCH4(%)	σN2O(%)
🟧	15	60	100	🟩	9	60	100
⬜	12	60	100	🟩	9	57	93
🟨	12	57	93	🟦	9	57	93
🟪	10	60	100	🟦	5	32	42

(b)

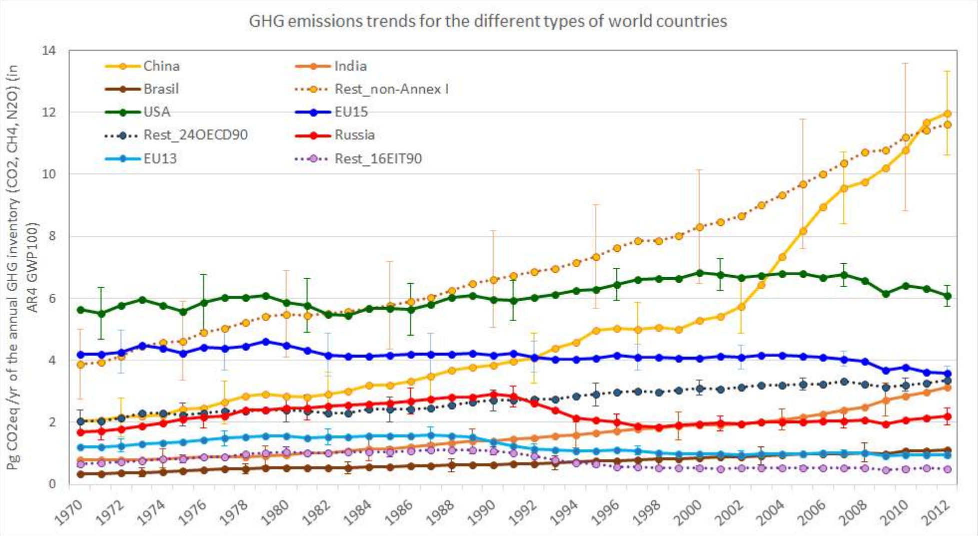


Figure 4: Annual greenhouse gas time-series 1970-2012 of EDGARv4.3.2 with periodic error bar indication for the different types of countries with top emitters: (i) non-Annex I countries with China, India, Brasil and Rest of non-Annex I countries, (ii) 24OECD90 countries with USA, EU15 and the remaining 8 OECD countries of 1990, (iii) 16EIT90 countries with Russia, EU13 and the remaining 2 newly independent Eurasian states.

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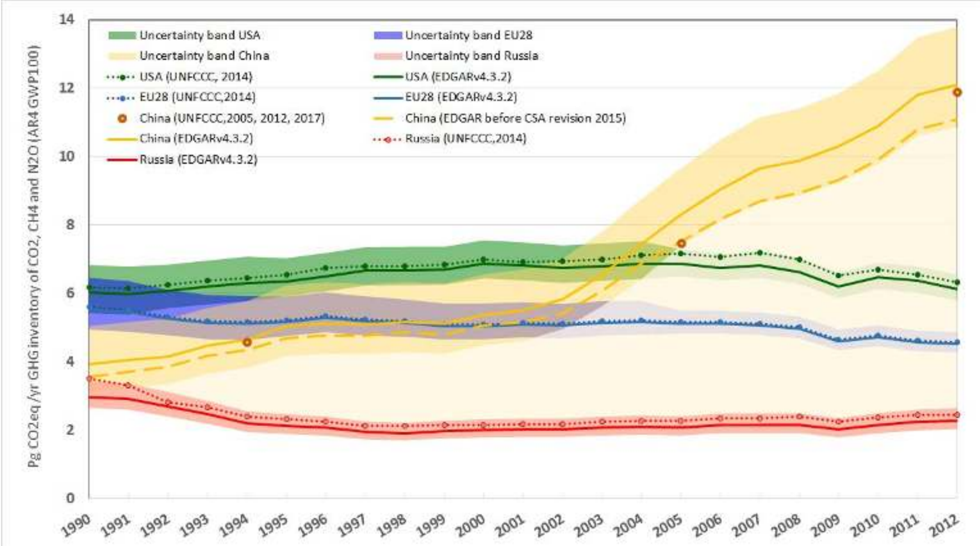


Figure 5: GHG emissions of largest emitting countries and regions (USA, EU28, Russia, China) of EDGARv4.3.2 (solid line) with their uncertainty band compared to the reported UNFCCC time-series of 2016 (dotted line). For China, two inventories were reported by national communications (1994, 2005) and a biennial update in 2017 added a new inventory value for 2012. The dashed yellow line gives the EDGARv4.3.1 estimate of the Chinese GHG emissions using the energy statistics before the Coal Statistics Abstract (CSA) revision of October 2015.

Table 3: Intercomparison of eight global CO_2 datasets with regard to their spatial and temporal coverage and their estimate of the global CO2 totals per source for 2010 (and 2007 for PKU-FUEL and ODIAC).

CO_2 totals in Pg/yr for 2010	**EDGARv4.3.2**	**GCP**	**PKU-FUEL (-CO2)**	**ODIAC**
Time-series	1970-2012 , fast track to 2015	1959-2015	2007	1980-2007
spatial resolution	0.1° x 0.1°		0.1° x 0.1°	1*km* x 1*km*
temporal resolution	monthly	annual	annual	Annual
Geo-coverage	226 countries	global	223 countries	
activity split	150 activities, 42 fossil and 15 bio fuels)	5 main sectors, 42 fuel types	64 fuel types	
fossil fuel combustion	30.5	Bottom-up estimate: 34.5 [Top down estimate: 35.6]	28.71	
non-combustion	3.1			
CO2 totals in Pg/yr for 2010	**CDIAC**	**EIA**	**IEA**	**BP**
Time-series	1751-2014	1980-2011	1971-2014	1965-2015
temporal resolution	annual	annual	annual	Annual
Geo-coverage	224 countries	224 countries	137 countries, 3 regions	67 countries, 5 regions
activity split-up	5 main sectors, 42 fuel types	6 main sectors, 42 fuel types	64 activities, 42 fossil and 15 bio fuels)	8 activities, 3 fossil and 3 other fuel types
fossil fuel combustion	32.7	31.6	31.0	33.5
non-combustion	1.6			

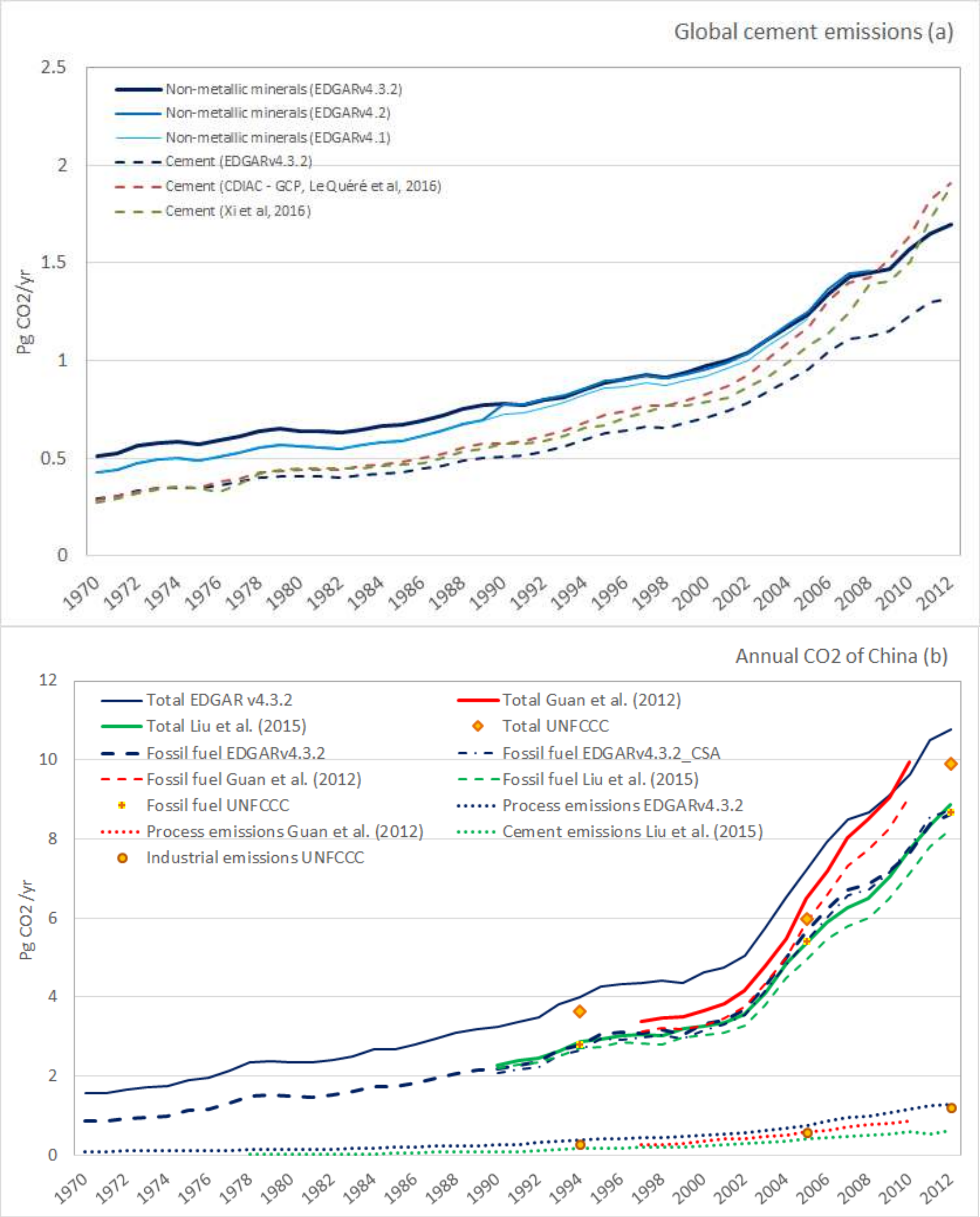
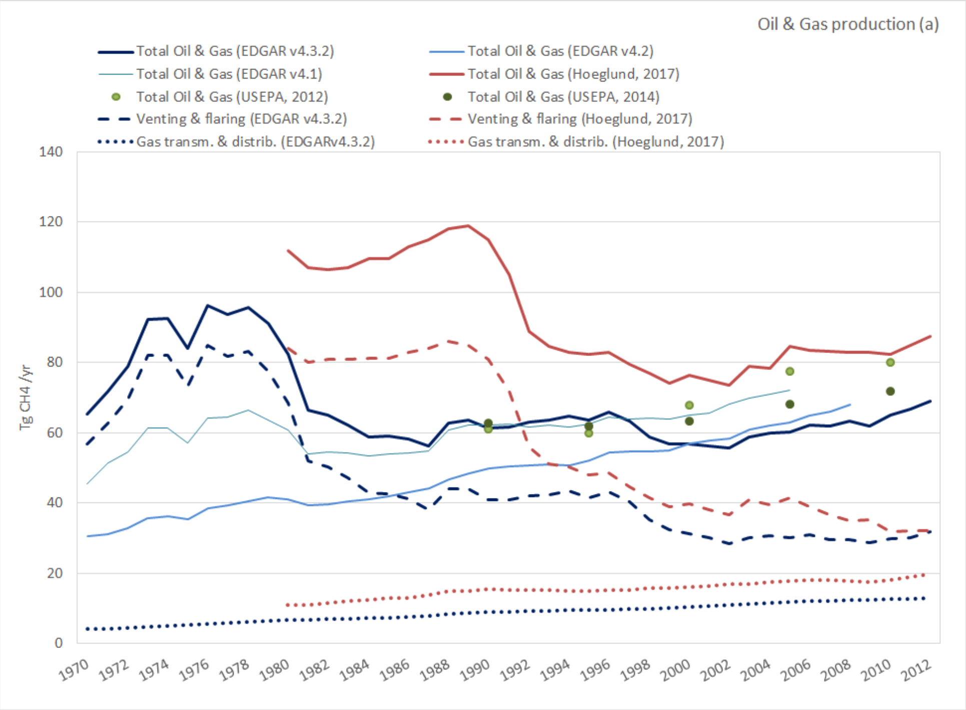


Figure 6: Intercomparison of CO_2 emissions trends estimated by EDGAR and by others with: (a) details for cement process emissions globally with data of Le Quéré et al. (2016) and Xi et al. (2016), (b) details for China's sector-specific emissions with data of Guan et al. (2012) and Liu et al. (2015). Total is for all datasets subdivided into Fossil fuel combustion and Industrial process emissions (i.e. non-combustion industrial emissions, including cement)

Table 4: Intercomparison of the global total Pg CH_4 in 2010 by EDGARv4.3.2 and by four other global emission inventories: USEPA (2012), GAINS-ECLIPSEv5 CH_4 of Höglund-Isaksson et al. (2015), Kirschke et al. (2013) and the global methane budget of Saunois et al. (2016). Note that the sector-specific global total is given in Tg CH4/yr for 2010 and in brackets for 2000. USEPA 2010 value is projected. For Kirschke, instead of 2010 (2000) we used the Maximum (Minimum) of the 2000-2009 range. For Saunois we used instead of 2010 (2000) the 2012 value (mean value of the 2000-2009 range).

CH4 totals in Tg/yr for 2010 (2000)	**EDGARv4.3.2**	**USEPA (2012)**	**GAINS ECLIPSEv5 (2014)**	**Kirschke et al. (2013) Bottom up [Top down]**	**Saunois et al. (2016) Bottom up [Top down]**
Time-series	1970-2012	1990-2005 (projected to 2030)	1990-2010	1980-2009	2000-2012
spatial resolution	0.1°x0.1°	none	1°x1°		
temporal resolution	monthly	annual	annual	annual	Annual
Geo-coverage	227 countries	224 countries	77 countries & 5 regions	global	global
Agricultural sector	154 (137)	147 (136)	129 (123)	Bottom up: 219 (263) [Top down: 286 (204)]	Bottom up: 197 (190) [Top down: 200 (183)]
Waste & wastewater	67 (59)	65 (58)	51 (46)		
energy and fossil fuel production	121 (96)	129 (107)	144 (116)	Bottom up: 105 (85) [Top down: 123 (77)]	Bottom up 164 (142) [Top down: 147 (136)]
Other	21 (18)		19 (17)	-	-
Total	342 (293)		342 (302)	Bottom up: 368 (304) [Top down: 409 (273)]	Bottom-up: 370 (338) [Top down: 347 (319)]



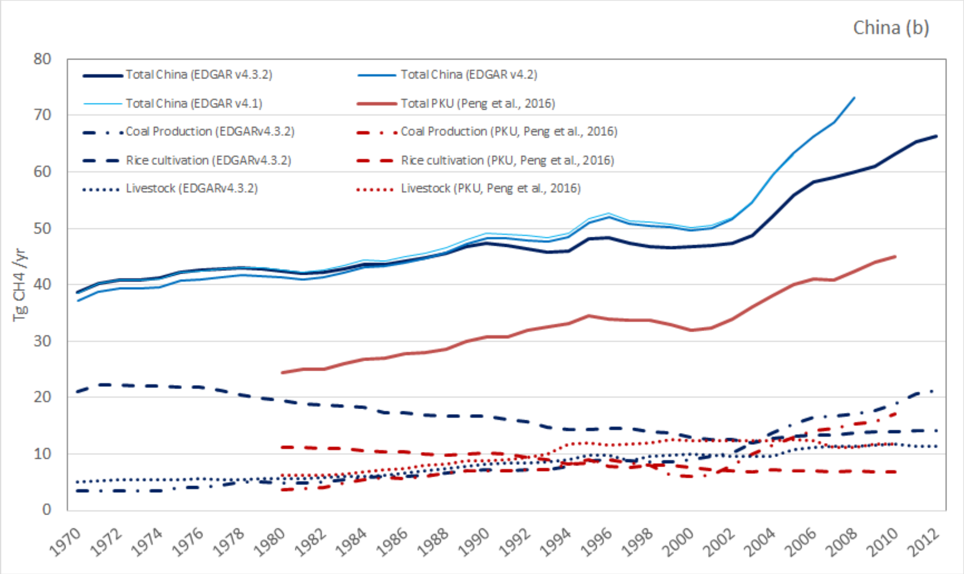


Figure 7: Intercomparison of CH_4 emissions trends estimated by EDGAR and by others with: (a) details for the CH4 venting for oil and gas extraction, transmission and distribution with data of Höglund-Isaksson (2017) and (b) details for China's sector-specific emissions with data of Peng et al. (2016)

Table 5 Intercomparison of the global (EU27) total Tg N2O in 2005 by EDGARv4.3.2 and by other European and global inventories; The European N Assessment of Leip et al. (2011) for EU27, GAINS for Europe of Winiwarter (2005) and Hoeglund-Isaksson et al. (2010) and USEPA for the global total(2010)

N2O totals in Tg/yr for 2005 global (EU27)	**EDGARv4.3.2**	**N-Budget**	**GAINS**	**USEPA (2012)**
timeseries	1970-2012	2000-2007	1990-2005 (projected to 2030)	1990-2005 (projected to 2030)
spatial resolution	0.1° x 0.1°	1*km* x1*km*		
temporal resolution	monthly	annual	annual	annual
geocoverage	226 countries	27 countries in Europe	39 countries in Europe	global
Agriculture	4.63 (0.43)	(0.68)	(0.87)	1.95
Non-Agriculture	2.54 (0.37)	(0.31)	(0.44)	8.91
Total	7.16 (0.80)	(1.08)	(1.30)	10.86

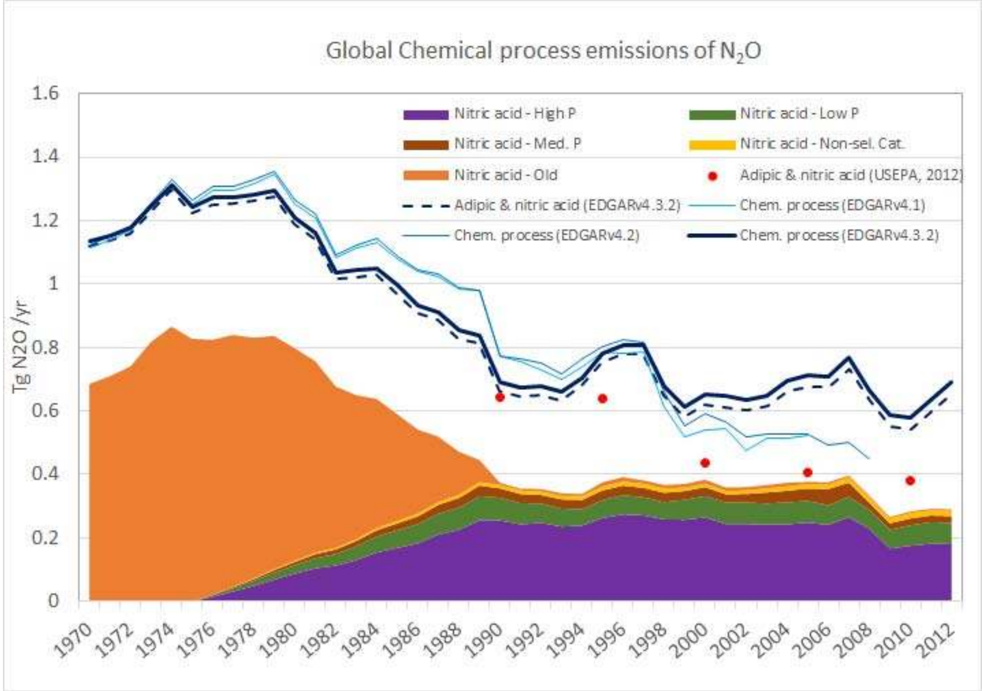


Figure 8: Global N2O emissions trends for chemical processes, which are mainly originating from Nitric and Adipic Acid Production (aside of smaller contributions from Glycoxal and Caprolactam Production) The coloured area illustrates the penetration of technology for nitric acid production (with High Pressure plants, Medium Pressure plants, Low Pressure plants, plants with Non-Selective Catalytic Reduction and Old plants) to reduce the emissions. 5

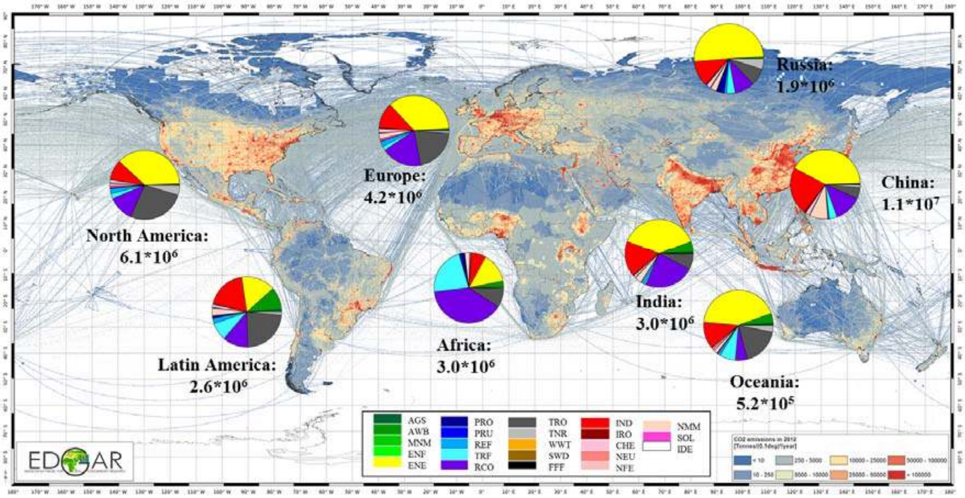


Figure 9: CO_2 emission grid-map and relative contribution of EDGAR sectors in world regions (pie charts) for 2012. The represented CO2 emissions include also those from short-cycle carbon of biofuel combustion and agricultural waste burning. 10

Table 6a - Global and regional GHG emissions (in ktons and tons/person) for the year 2012. CO$_{2eq}$ emissions have been calculated including only CO$_2$ from long-cycle carbon only, CH$_4$ and N$_2$O.

year 2012	CO2 long cycle C	CO2 short cycle C	CH4	N2O	CO2eq (AR5)	CO2eq (AR4)	CO2eq (SAR)	CO2eq (AR4)/cap
Canada	5.64E+05	5.33E+04	4.68E+03	1.23E+02	7.28E+05	7.18E+05	7.00E+05	20.6
USA	5.20E+06	3.10E+05	2.58E+04	9.44E+02	6.18E+06	6.13E+06	6.04E+06	19.5
Mexico	4.84E+05	5.23E+04	5.20E+03	3.73E+02	7.29E+05	7.26E+05	7.09E+05	5.9
Rest Central America	1.71E+05	9.63E+04	3.60E+03	8.54E+01	2.95E+05	2.87E+05	2.73E+05	3.3
Brazil	4.73E+05	5.20E+05	1.92E+04	5.63E+02	1.16E+06	1.12E+06	1.05E+06	5.5
Rest South America	6.61E+05	1.59E+05	1.62E+04	4.07E+02	1.22E+06	1.19E+06	1.13E+06	5.8
Northern Africa	4.87E+05	1.68E+04	7.20E+03	1.40E+02	7.25E+05	7.08E+05	6.81E+05	4.1
Western Africa	1.71E+05	9.14E+05	1.57E+04	2.77E+02	6.83E+05	6.45E+05	5.86E+05	1.5
Eastern Africa	5.51E+04	5.53E+05	1.15E+04	3.33E+02	4.65E+05	4.42E+05	4.00E+05	1.6
Southern Africa	4.49E+05	3.95E+05	8.21E+03	1.94E+02	7.30E+05	7.12E+05	6.82E+05	3.5
OECD Europe	3.08E+06	3.74E+05	1.83E+04	7.10E+02	3.78E+06	3.75E+06	3.68E+06	9.1
Central Europe	8.51E+05	1.08E+05	6.41E+03	2.39E+02	1.09E+06	1.08E+06	1.06E+06	8.7
Turkey	3.40E+05	3.37E+04	3.76E+03	1.56E+02	4.87E+05	4.80E+05	4.67E+05	6.4
Ukraine +	3.93E+05	2.45E+04	3.46E+03	1.61E+02	5.32E+05	5.27E+05	5.15E+05	9.0
Asia-Stan	4.52E+05	6.00E+03	7.75E+03	1.12E+02	6.99E+05	6.79E+05	6.50E+05	10.6
Russia +	1.82E+06	3.29E+04	1.84E+04	2.35E+02	2.39E+06	2.35E+06	2.28E+06	14.7
Middle_East	1.84E+06	8.65E+03	2.05E+04	2.17E+02	2.48E+06	2.42E+06	2.34E+06	10.7
India +	2.34E+06	1.19E+06	4.70E+04	1.10E+03	3.95E+06	3.85E+06	3.67E+06	2.3
Korea	6.61E+05	1.08E+04	2.41E+03	5.26E+01	7.43E+05	7.37E+05	7.28E+05	9.9
China +	1.03E+07	8.50E+05	6.76E+04	1.78E+03	1.26E+07	1.25E+07	1.22E+07	9.0
South-East Asia	8.03E+05	5.43E+05	1.93E+04	2.97E+02	1.42E+06	1.37E+06	1.30E+06	3.8
Indonesia +	4.53E+05	3.28E+05	1.21E+04	2.58E+02	8.61E+05	8.33E+05	7.88E+05	3.3
Japan	1.30E+06	5.36E+04	1.85E+03	7.56E+01	1.37E+06	1.37E+06	1.36E+06	10.8
Oceania	4.67E+05	4.90E+04	6.49E+03	2.07E+02	7.04E+05	6.91E+05	6.68E+05	22.7
Internat. Shipping	6.09E+05	1.49E+02	4.92E+02	8.44E+01	6.45E+05	6.46E+05	6.45E+05	0.1

Internat. Aviation	4.83E+05		3.38E+00	2.36E+01	4.89E+05	4.90E+05	4.90E+05	0.1
Totals	3.49E+07	6.68E+06	3.53E+05	9.15E+03	4.72E+07	4.64E+07	4.51E+07	6.5

Table 6b - Global sector-specific GHG emissions for the year 2012 (in ktons and tons/person). CO_{2eq} emissions have been calculated including only CO_2 from long-cycle carbon only, CH_4 and N_2O. *Note that emissions from the Supersonic aviation are available only till the year 2003, when the Concorde airplanes stopped flying.

EDGAR SECTOR	**DESCRIPTION**	**CO2** long cycle C	**CO2** short cycle C	**CH4**	**N2O**	**CO2eq (AR5)**	**CO2eq (AR4)**	**CO2eq (SAR)**	**CO2eq(AR4)/cap**
AGS	Agricultural soils	1.6E+05		3.8E+04	5.0E+03	2.5E+06	2.6E+06	2.5E+06	0.36
AWB	Agricultural waste burning		1.0E+06	1.8E+03	4.6E+01	6.2E+04	5.9E+04	5.2E+04	0.01
CHE	Chemical processes	6.8E+05		2.8E+02	6.9E+02	8.7E+05	8.9E+05	9.0E+05	0.13
ENE	Power industry	1.4E+07	4.9E+05	3.8E+02	2.8E+02	1.4E+07	1.4E+07	1.4E+07	1.95
ENF	Enteric fermentation			1.0E+05		2.9E+06	2.6E+06	2.2E+06	0.37
FFF	Fossil Fuel Fires	4.7E+04		1.5E+02	7.5E-01	5.2E+04	5.1E+04	5.1E+04	0.01
FOO_PAP	Food and Paper								0.00
IND	Combustion for manufacturing	5.5E+06	7.4E+05	5.6E+02	7.6E+01	5.6E+06	5.6E+06	5.6E+06	0.79
IRO	Iron and steel production	2.2E+05		5.2E+01		2.2E+05	2.2E+05	2.2E+05	0.03
MNM	Manure management			1.2E+04	3.4E+02	4.2E+05	4.0E+05	3.5E+05	0.06
NEU	Non energy use of fuels	2.5E+04				2.5E+04	2.5E+04	2.5E+04	0.003
NFE	Non-ferrous metals production	8.1E+04				8.1E+04	8.1E+04	8.1E+04	0.01
NMM	Non-metallic minerals production	1.7E+06				1.7E+06	1.7E+06	1.7E+06	0.24
PRO	Fuel exploitation	2.2E+05		1.1E+05	3.3E+00	3.2E+06	2.9E+06	2.5E+06	0.41
PRU_SOL	Solvents and products use	1.7E+05			8.6E+01	1.9E+05	1.9E+05	2.0E+05	0.03
RCO	Energy for buildings	3.3E+06	3.4E+06	1.4E+04	2.7E+02	3.7E+06	3.7E+06	3.6E+06	0.52
REF_TRF	Oil refineries and Transformation industry	1.8E+06	8.7E+05	6.0E+03	2.1E+01	2.0E+06	1.9E+06	1.9E+06	0.27
SWD_INC	Solid waste incineration	1.1E+04	1.5E+04	1.3E+03	4.0E+00	4.9E+04	4.5E+04	4.0E+04	0.01

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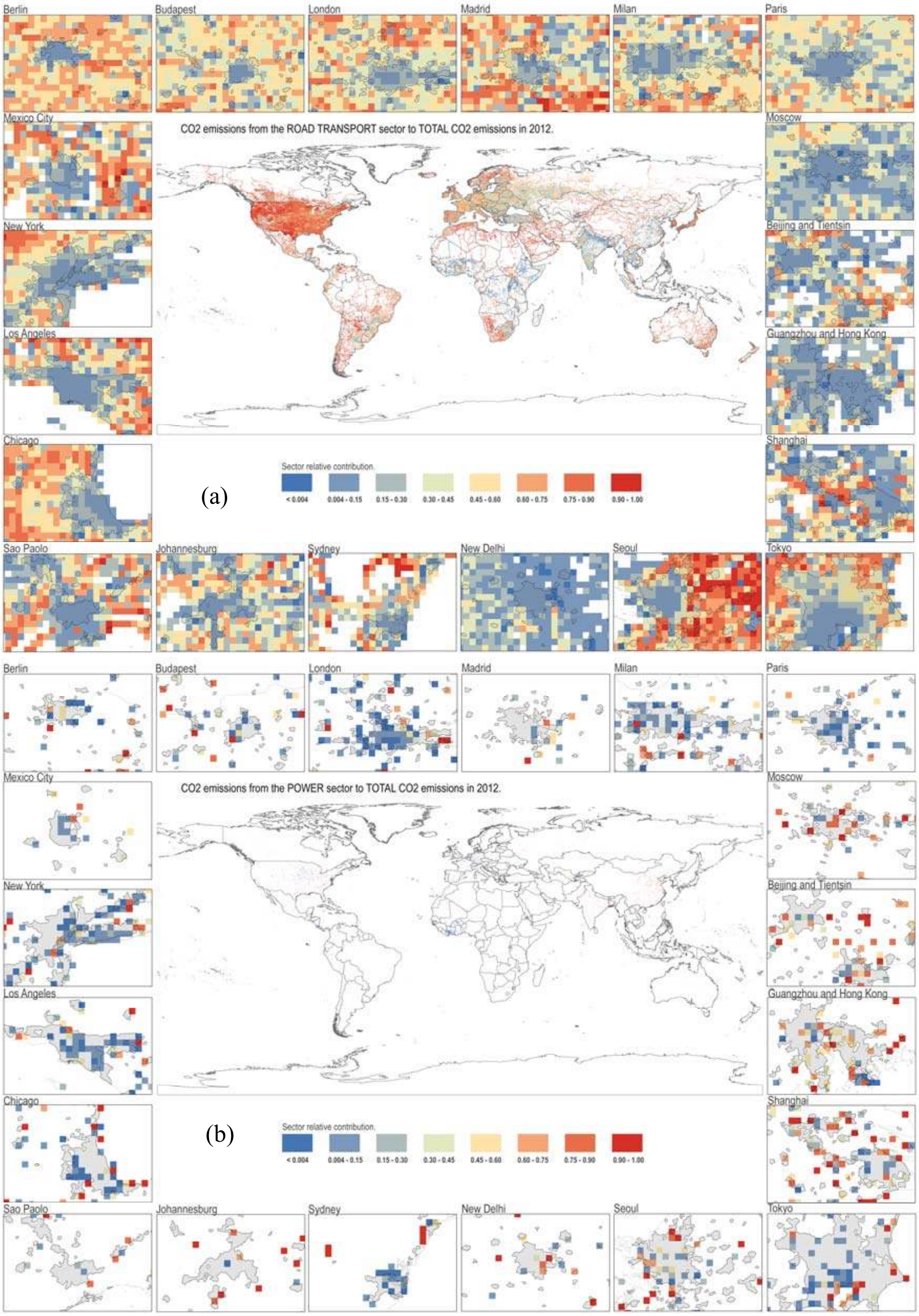
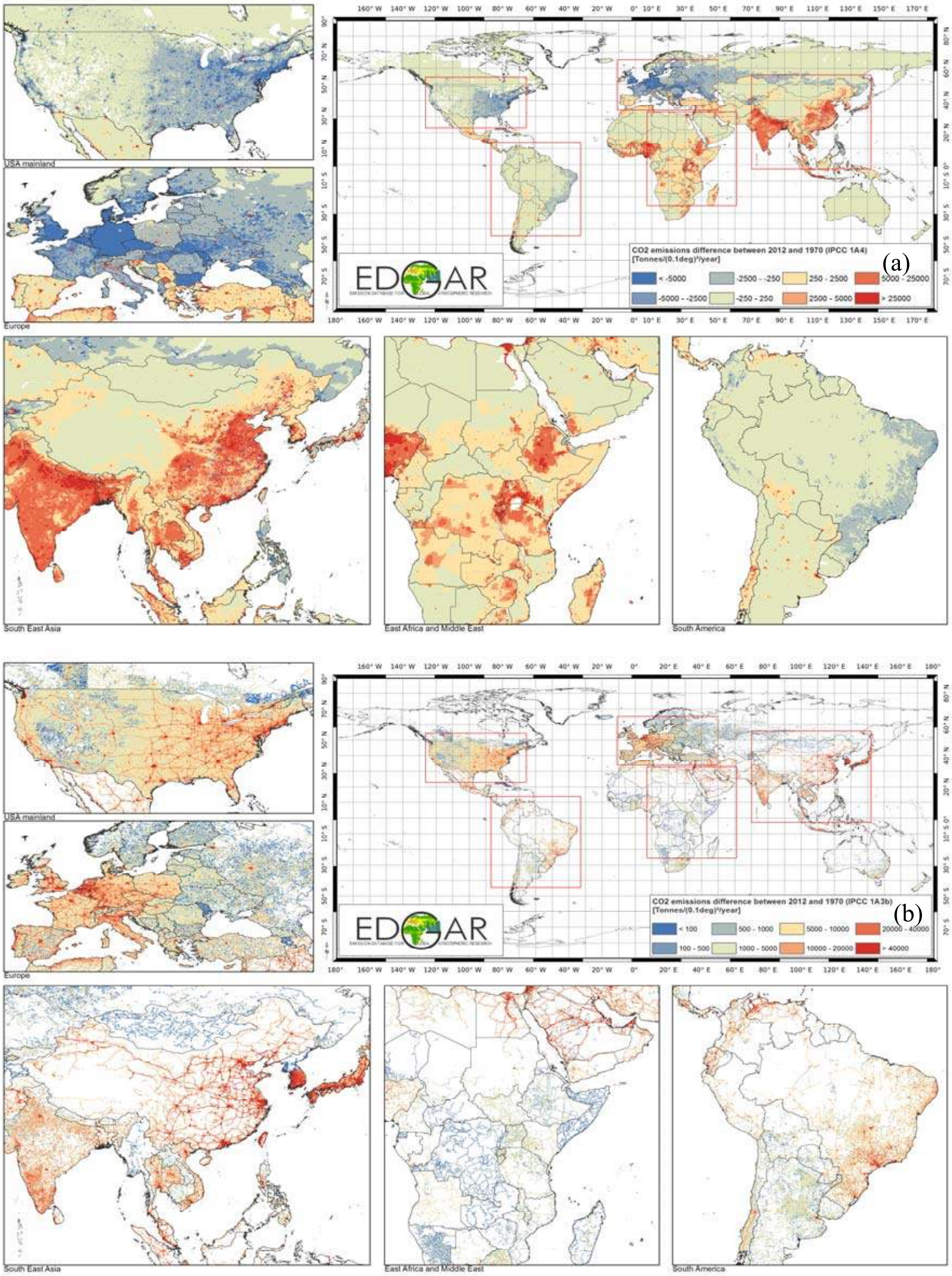
SWD_LDF	Solid waste landfills			2.9E+04	1.1E+01	8.2E+05	7.3E+05	6.2E+05	0.10
TNR_Aviation_CDS	Aviation climbing&descent	2.9E+05		2.0E+00	8.1E+00	2.9E+05	2.9E+05	2.9E+05	0.04
TNR_Aviation_CRS	Aviation cruise	3.9E+05		2.7E+00	1.1E+01	3.9E+05	3.9E+05	3.9E+05	0.06
TNR_Aviation_LTO	Aviation landing&takeoff	9.3E+04		6.5E-01	2.6E+00	9.4E+04	9.4E+04	9.4E+04	0.01
*TNR_Aviation_SPS	Aviation supersonic								
TNR_Other	Railways, pipelines, off-road transport	2.6E+05	7.5E+02	8.7E+00	3.8E+01	2.7E+05	2.7E+05	2.7E+05	0.04
TNR_Ship	Shipping	7.8E+05	1.6E+02	7.1E+01	2.0E+01	7.9E+05	7.9E+05	7.9E+05	0.11
TRO	Road transportation	5.4E+06	1.7E+05	8.0E+02	2.3E+02	5.5E+06	5.5E+06	5.5E+06	0.78
WWT	Waste water handling			3.8E+04	3.5E+02	1.2E+06	1.1E+06	9.1E+05	0.15
IDE	Indirect emissions				6.2E+02	1.6E+05	1.8E+05	1.9E+05	0.03
N2O	Indirect N2O emissions				1.1E+03	2.8E+05	3.2E+05	3.3E+05	0.04



5 **Figure 10: Zoom of CO_2 emission grid-maps over cities, representing the share of the road transport (a) and power plants (b) within the cities. The represented CO_2 emissions include also those from short-cycle carbon of biofuel combustion and agricultural waste burning.**



5 **Figure 11: Difference in CO₂ emissions from buildings (a) and road transport (b) between 2012 and 1970. The represented CO2 emissions include also those from short-cycle carbon of biofuel combustion and agricultural waste burning.**

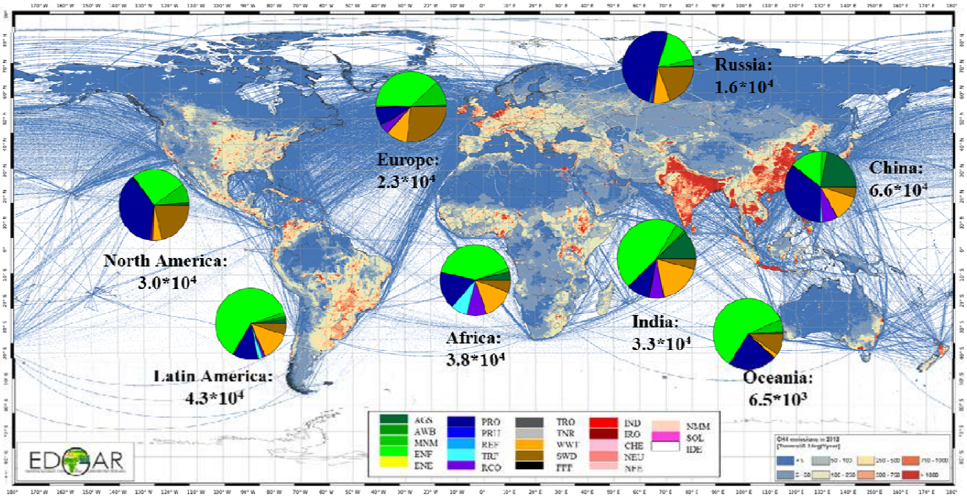
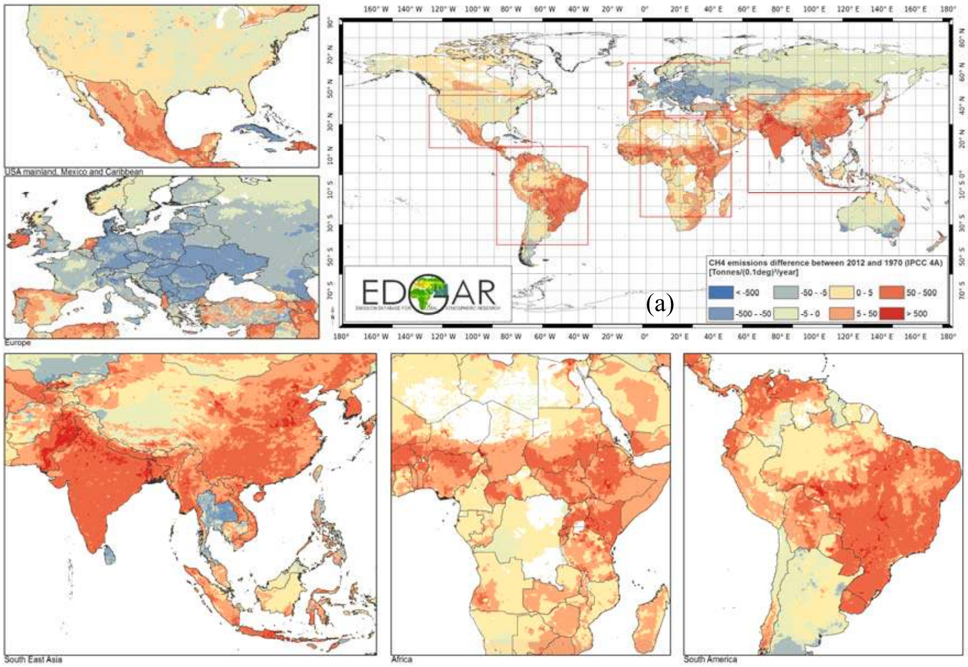


Figure 12: CH$_4$ emission grid-map and relative contribution of EDGAR sectors in world regions (pie charts) for 2012.



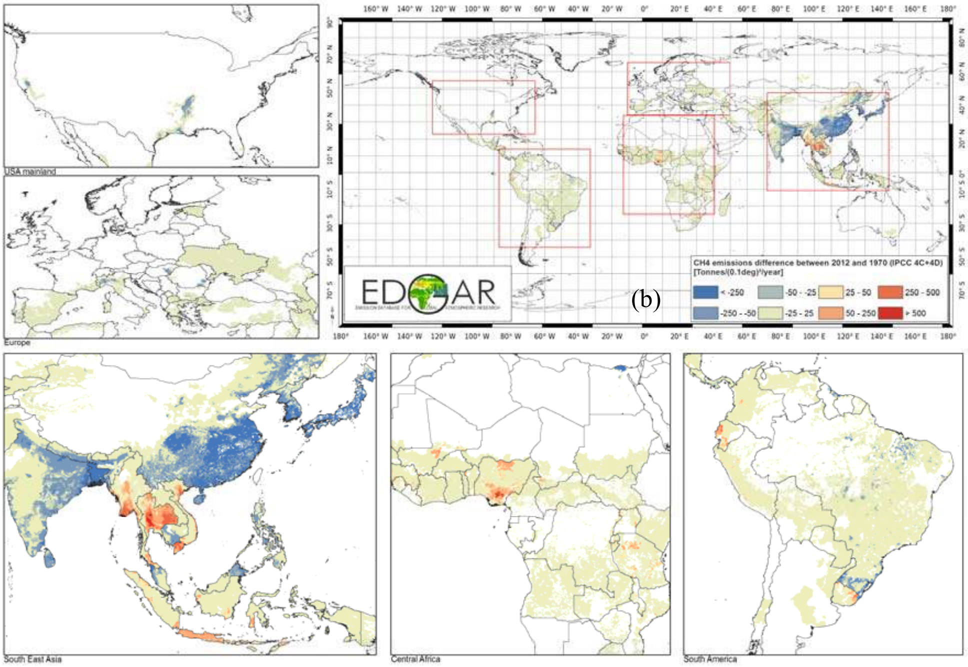


Figure 13: Difference in CH_4 emissions from enteric fermentation (a) and rice cultivation (b) between 2012 and 1970.

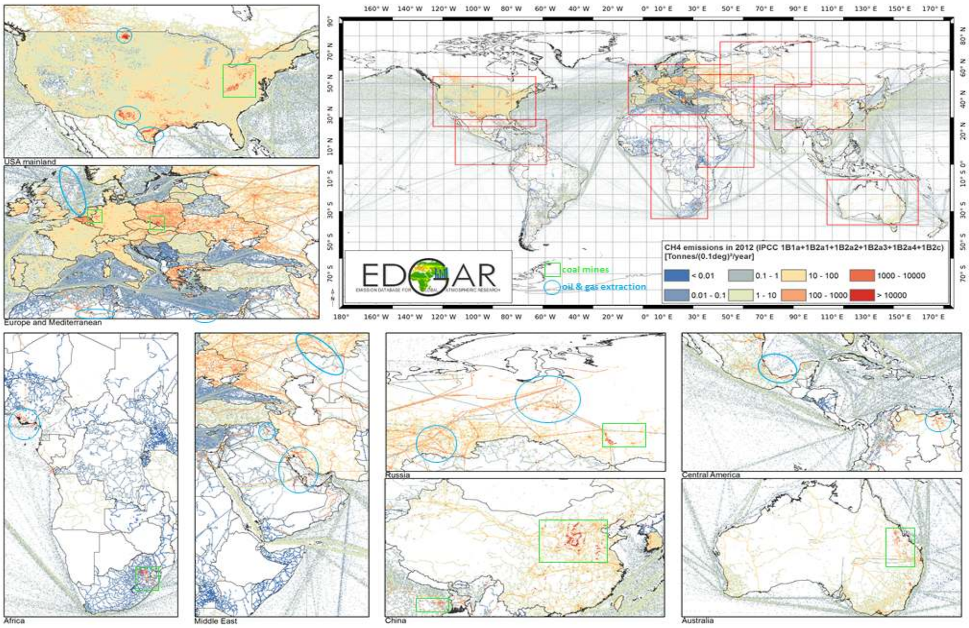


Figure 14: CH_4 emissions from fossil fuel production in 2012 with zoom on areas with intense coal mining (within green frame) and gas&oil production activities with venting (within blue circle). The shipping lines are not representing the transport emissions but the CH_4 leakage during transmission of oil tanker transport.

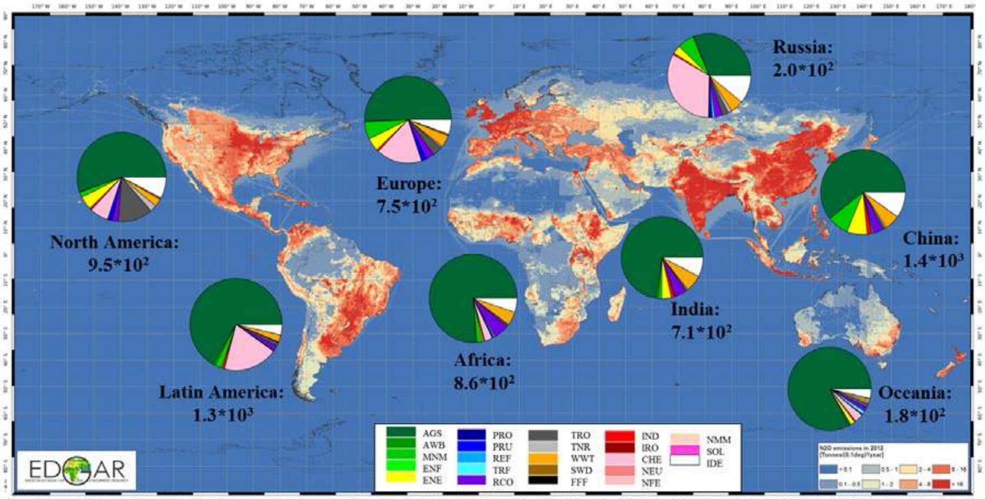
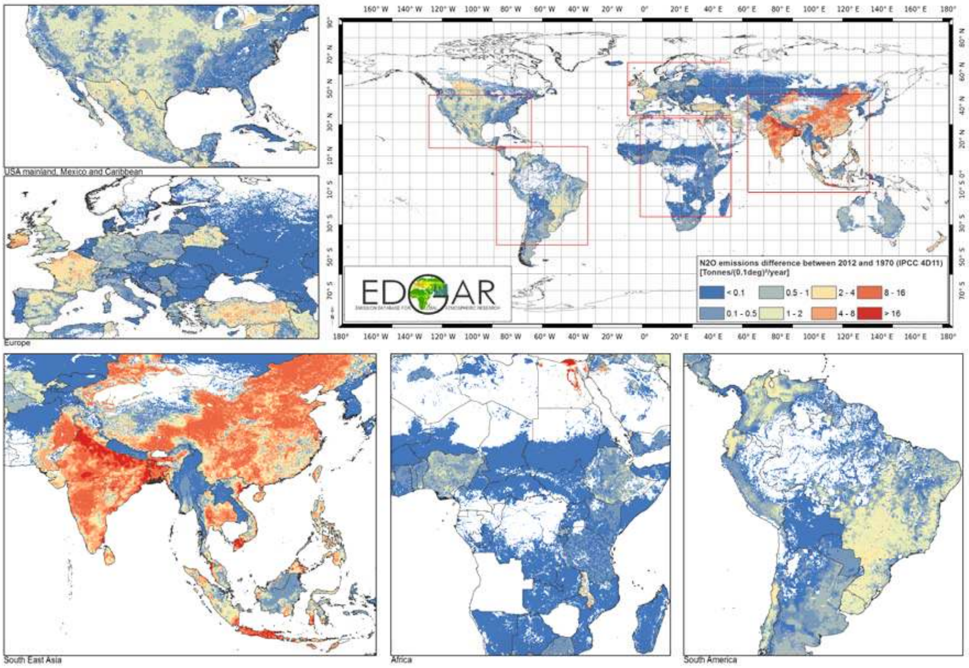


Figure 15: N_2O emission grid-map and relative contribution of EDGAR sectors in world regions (pie charts) for 2012.



5 **Figure 16: Difference between 2012 and 1970 in N_2O emissions from fertiliser use on agricultural soils.**