Response to **A. Sellar (Referee)**

General comments:

Firstly I congratulate the CEDS team on what has clearly been a monumental effort, and one which will benefit the climate modelling community greatly. On this note, it would be nice to say a little more about the CEDS project itself in the introduction: e.g. what is the "community" aspect, what is the formal project goal.

Thank you for your kind comments. The following text on "community" has been added to the summary section:

With release of this data set, and soon the entire data system, it is our intention that further improvements will be made through feedback from the global emissions inventory community. The CEDS data system, including R code and all input data other than the IEA energy balances, is being prepared for public release in fall 2017 through the gitHub collaboration website. This will facilitate community comment, and direct contributions to improving these emissions data. The next data release is planned for Fall 2017, which will extend the time series to 2016 and correct, to the extent possible, any known issues with the dataset. We aim to continue annual updates in subsequent years. We welcome comments, including notes on any potential inconstancies or relevant new data sources, so that that these data can be improved in future releases.

The manuscript gives a detailed and thorough account of the methodology. Some of the detail could perhaps be moved to the supplementary material to reduce the length of section 2. This is merely a suggestion: I leave this at the authors' discretion.

Thank you for the suggestion. We agree that the paper is a bit long, and we have moved a few secondary points to the supplement, but during our internal review process found that we received many methodology questions, as many readers (unless motivated by a specific highly detailed questions) are unlikely to page through the extensive supplement.

Please include some comparison of the spatial distribution of emissions against Lamarque et al. in section 3, at least for the species totals, focusing on 1850 and 2014 since these are important years for CMIP6.

We have added a section showing gridded data, as well as comparisons of gridded data between Lamarque et al 2010 and CEDS data. We have included additional gridded figures in the SI as well.

The discussion on uncertainty is very useful, and I am pleased to see that "quantitative uncertainty analysis" and emissions ensembles will be included with future data releases. This will assist in understanding sources of uncertainty in historical radiative forcing due to composition changes; given that this is a major outstanding question in climate modelling I would urge the CEDS project to place high priority on this development.

Thank you. We agree. After the upcoming public release of the data system, uncertainty is a high priority.

Finally, given the problems in the 2016 data release which emerged after this discussion paper was published, the manuscript should be updated to refer to the methodological changes which have been applied for the 2017 release, and to summarize the impact of these changes.

We've added a section in the appendix detailing the changes in the various releases of the gridded data.

Specific comments and suggestions:

P2 L53: "(sometimes also as RCP historical data)" this is not a particularly meaningful phrase. I would suggest using only the name "CMIP5 dataset" for the collective historical and future dataset.

This text has been changed to:
"This data is also used as the historical starting point for the Representative Concentration Pathways (RCP) scenarios (van Vuuren et al., 2011) and in some research communities is referred to as the RCP historical data. In this article it is referred to as the CMIP5 data set."

P2 L83: "Preindustrial data (CEDS-v2016-06-18), 1750 – 1850, were released in June 2016 and CMIP6 historical data". Insert date range 1850-2014 for historical data.

We have added a section in the appendix, A2.2 that explains versions of CEDS releases. The following text appears in the appendix of the manuscript:

> There have been several releases of the CEDS gridded data. The underlying emissions by country, sector and fuel have been identical in all of these releases, as are total emissions by country and gridding sector (with the exception of small changes in 1850 emissions noted below).
>
> **v2016-05-20**: Pre-industrial 1750-1850 data release
>
> **v2016-06-18**: 1851 – 2014 data
>
> **v2016-06-18-sectorDim**: Re-release of both preindustrial and 1851 – 2014 in a new netCDF format with sectors as an additional dimension in the data variable. This reformatting was necessary due to a limitation that was discovered within the ESGF system summer 2016. The reformatted data were released early Fall 2016
>
> **2017-05-18**: Re-release of entire dataset in order to correct two gridding errors discovered by users. 1) Inconsistent emission allocation to spatial grids within countries that resulted in incorrect spatial allocations and some large discontinuities in the gridded data. These issues were particularly apparent in spatially large countries such as the USA and China. 2) Minor inconsistencies in seasonal allocation, resulting largely in emissions that were too high in February. Total annual emissions within each country were not impacted by either of these issues.

Emissions are also fully consistent across 1850 in this release. There were small discontinuities in 1850 between the CEDS CMIP6 preindustrial release (v2016-06-18) and the later full CEDS release (v2016-07-26) due to updates in the data system. These differences are 0.5% for all species (except NMVOC which reaches 1.5%). In absolute terms these differences are very small (relative to, for example, open biomass burning emissions) and will not have a significant impact on simulation results.

A link to further examination of these issues, including comparison maps and time series comparisons, can be found at the project web site (globalchange.umd.edu/CEDS).

P3 L97: This list of 6 phases would be clearer as numbered bullet points (i.e. an {enumerate} environment in LaTeX).

This change has been made. Thank you.

P4 L113: This seems like a key methodological difference from Larmarque et al: it would be good to say something about the impact this difference has on the resulting dataset.

This is a large change in methodology. First, it allows us to extend estimates forward over recent years by using recently updated energy data. Second it allows us to use more detail in historical years by modeling fuel use and EFs separately, which has had an impact on NOx and CO emissions from residential biomass burning for example. While these impacts are not explicitly noted in this section of the paper, we feel the rest of the paper has highlighted these differences, specifically the section on comparisons to the CMIP5 (*Larmarque et al*) dataset. A major advantage of this method is also that it can more consistency capture trends over time, mentioned here in the text, and which results in some changes in recent trends discussed later in the comparison with the CMIP5 dataset.

P5 L160: Suggest "available" -> "documented" or "detailed"

Thank you. The following text now appears in the manuscript:

Mapping of IEA products to CEDS fuels is **provided** in Sect. A3.

P6 L180: "Several other changes were made, such as". Clearly this paper cannot list all such changes, but from a methodological perspective, where is the full set of changes documented? In the CEDS code, or accompanying documentation?

Most, if not all of these assumptions are detailed in the Data and Assumption Supplement. All detailed methods (e.g. code), assumptions, and data will also be available with the open source release of the system. This is detailed in the manuscript in additional text describing the release of the system, as well as existing text describing the substantial supplemental information available to download with the manuscript.

P10 L345: "with a time and sector specific options ...". Delete "a".

This change has been made. Thank you

P12 L396: "Emissions from mineral and manure emissions are often inconsistently reported;

3B_Manuremanagement and 3D_Soil-emissions together, so CEDS total estimates should be reliable". I think some text is missing here.

This has been fixed. Thanks.

P13 L408: "Gridded emissions are aggregated to 9 sectors for final distribution". Does "final distribution" refer to the temporal distribution described in the next sentence? Please make this clearer. Also, why use the intermediate sectors for spatial distribution and the 9 sectors for temporal distribution?

Emissions are distributed over space using the intermediate gridding sectors. Seasonality is added using the 9 final gridding sectors. These steps in aggregation are determined by the level of detail of the proxy data and seasonality profiles. We've rearranged and added some language to make this more clear in the manuscript. Thank you.

P14 L424: This seems to be repeating what was said on P13 L 411.

Thanks. We've moved some text around so it is less repetitive.

P18 L522: missing "due" after comma?

Thanks. This change has been made.

P23 L690: "In future versions of CEDS, quantitative uncertainty analysis will be included for all time periods, but is not complete as of the CMIP6 data version." Does this mean that there is partial uncertainty information in the CMIP6 data version, or none because you will wait for complete information before publishing any? If the former, please say something about the quantitative methodology.

There is no quantitative uncertainty analysis at this time other than what is already in the literature. (The text has been revised to refer to an existing literature summary.)

P23 L694: "emissions concentrations are observed". Would "near-source concentrations" be a more accurate description?

We would like to note that comparison to both near-source and far field observations can be helpful in comparisons such as these, and we have compared to both in the paper (Hassler et al. 2016 and Kanaya et al. 2016).

Response to Anonymous Referee #1

In this paper, the authors document the methodology used to develop a new historical (1750-2014) short-lived species emissions data set for use by global chemistry-climate models for the upcoming Coupled Model Intercomparison Phase 6 (CMIP6). The paper provides detailed information on input data sets (e.g., emissions factors, activity data, population) and steps applied to generate the new emissions trends in Community Emissions Database System. The authors also compare this new dataset with existing emission inventories to place CEDS emissions in the context of existing data sets.

Emissions inventories provide crucial input data for global chemistry-climate models to simulate the spatial and temporal distributions of short-lived pollutants many of which are also climate forcers. Although gridded emissions inventories existed prior to the inventory of Lamarque et al (2010), there was a lack of consistency in the use of these products by different global modeling groups participating in multi-model intercomparisons. Development of a global gridded emissions inventory for not just the present conditions but going back in time is a major undertaking. I am sure the global chemistry- climate modeling community would be very appreciative of the service provided by the authors in not only updating the previous extensively used inventory (Lamarque et al., 2010), but also creating a consistent, transparent, and trackable process that can hopefully be sustained going forward. The paper is generally well-written and is appropriate for GMD.

My main comment on the paper is that the authors do not provide any comparisons of the spatial distribution of the gridded emissions against existing gridded products. A panel plot with maps of present day (e.g., 2010) species emissions should be included in the main text. Some discussion of how they compare with the spatial distributions in existing inventories would be helpful.

Thank you for your kind comments. A new section has been added to Section 3, titled "Gridded Emissions" which includes a panel figure of gridded emission of CEDS total emissions estimates for all 9 emission species in 2010.

Additionally a discussion of the differences between CEDS grids and Lamarqe et al (2010) grids for 1850 and 2000 have been added to CMIP5 Comparison section. A figure showing side by side gridded maps of the differences for EM for 1850 and 2000 has been added to the main text. Difference maps for all other emissions species for both 1850 and 2000 have been included in the supplemental figures document.

Below are some specific comments to help improve the paper:

Specific comments:

P2: Suggest arranging the discussion of existing emission inventories chronologically. EDGAR has a long history of developing emissions data set and was available much before the inventory of Lamarque et al (2010) (referred to as L2010 hereafter). In fact, the EDGAR informs the L2010 and the work described in this paper.

Thank you for this comment. Paragraphs discussing EDGAR and Lamarque 2010 data (L49 - 76) have been swapped so that this section discusses EDGAR and Gains, followed by Lamarque 2010 data.

L84: What is the time period for the historical data?

We have added a section in the appendix, A2.2 that explains versions of CEDS releases. The following text appears in the appendix of the manuscript:

> There have been several releases of the CEDS gridded data. The underlying emissions by country, sector and fuel have been identical in all of these releases, as are total emissions by country and gridding sector (with the exception of small changes in 1850 emissions noted below).
>
> **v2016-05-20**: Pre-industrial 1750-1850 data release
>
> **v2016-06-18**: 1851 – 2014 data
>
> **v2016-06-18-sectorDim**: Re-release of both preindustrial and 1851 – 2014 in a new netCDF format with sectors as an additional dimension in the data variable. This reformatting was necessary due to a limitation that was discovered within the ESGF system summer 2016. The reformatted data were released early Fall 2016
>
> **2017-05-18**: Re-release of entire dataset in order to correct two gridding errors discovered by users. 1) Inconsistent emission allocation to spatial grids within countries that resulted in incorrect spatial allocations and some large discontinuities in the gridded data. These issues were particularly apparent in spatially large countries such as the USA and China. 2) Minor inconsistencies in seasonal allocation, resulting largely in emissions that were too high in February. Total annual emissions within each country were not impacted by either of these issues.
>
> Emissions are also fully consistent across 1850 in this release. There were small discontinuities in 1850 between the CEDS CMIP6 preindustrial release (v2016-06-18) and the later full CEDS release (v2016-07-26) due to updates in the data system. These differences are 0.5% for all species (except NMVOC which reaches 1.5%). In absolute terms these differences are very small (relative to, for example, open biomass burning emissions) and will not have a significant impact on simulation results.
>
> A link to further examination of these issues, including comparison maps and time series comparisons, can be found at the project web site (globalchange.umd.edu/CEDS).

L85-L87: The chemical formulas for these species are first used on L55 without defining them. Suggest moving the full names closer to where the formulas are used for the first time in the text.

Thank you for pointing this out, Appropriate explanations of chemical formulas were moved to L55 where they first appear.

L102-103: At what point is the seasonality added?

The following text was changed to specify that seasonality is added to gridded data in the final step: "…6) gridded emissions with monthly seasonality are produced from aggregate estimates using proxy data.." There is additional explanation of this process in section 2.6 Gridded Emissions.

Figure 1, captions: replace "produces" with "products" on P4.

Thank you. This change was made

L116: What does "energy balance statistics" mean here?

We are refereeing to detailed IEA energy statistics. The following change has been added for clarification:

"energy statistics"

L117: A quick search on google tells me that there are 196 countries in the world (not considering Taiwan separately would bring the count down to 195). Am I missing some- thing? Could the authors please provide a color coded map of countries considered in the work?

We clarify in the revised manuscript that we consider a number of regions whose exact status might not be clear. The most definitive categorization is given by the UN, and we use UN population data as the basis of our current "country" disaggregation. As noted in the manuscript, we are using the term "country" regardless of the exact status of any particular entity.

The supplemental information includes a csv file which contains a list of all the "countries" used here along with their common name, ISO code, and mapping to countries and regions from other data sets such as the IEA energy data. Many of these "countries" would not be visible on a global color coded map as they are small islands and territories.

The following change has been added to the manuscript for clarification:

"CEDS estimates emissions for 221 **regions** (and a global region for international shipping and aircraft), ... **"Regions" refers to countries, regions, territories, or islands and are listed, along with mapping to regions and ISO codes in the supplemental files; they will henceforth be referred to as "countries"."**

L123: A reference is needed for the IPCC guidelines and Nomenclature for reporting document.

This reference has been added. Thank you.

L137: What kind of "additional effort" would be needed? Please elaborate.

These efforts are briefly described in the future work section of the manuscript. The following text has been added to the manuscript to clarify:

Greater disaggregation for these sectors would improve these estimates, but will require additional effort**, described in Sect.5 Limitations and Future work.**

L140-141: Please elaborate on the "confidentiality issues." As I understand, sector level emissions are provided in the gridded files, so I am confused by this statement.

The text has been clarified on this point. We note that other global emissions data providers, such as EDGAR, are subject to a similar limitation in terms of releasing emissions data at the level of fuel, sector, and country.

The core outputs of the CEDS system are country-level emissions aggregated to the CEDS sector level. Emissions by fuel and **detailed CEDS** sector are also available within the system for analysis, although these are not released because this could violate the terms of our use of the IEA energy statistics. (This is the same reason other global inventory data, such as EDGAR, also do not release data by sector, country, and fuel). Emissions are further aggregated and processed to provide gridded emissions data with monthly seasonality, detailed in Sect. …

P4L143: What is meant by "emission control degradation?"

"Emission control degradation" refers to certain emission control technologies that may become less effective overtime, for example an old catalytic converter in an old car may be less effective than a new catalytic in an old car. The following text has been changed in the manuscript for clarification:

For example, CEDS does not include a representation of vehicle fleet turnover and emission control degradation (*e.g.* **the effectiveness of catalytic converters over time**) or multiple fuel combustion technologies that are included in more detailed inventories.

L161-162: Does the population data used to disaggregate energy data for CEDS countries change with time? Describe any assumptions made. Also, please provide a reference for the population data set used.

As described in section 2.2.2 and further the supplement, a full time series over 1750-2014 of population estimates for all CEDS "countries" is developed by merging several data sources.

However, this explanation incorrectly describes the methodology we used for disaggregating IEA aggregate regions. Aggregate IEA data were disaggregated using CDIAC data, not population data. The following text now appears in the manuscript:

Data for a number of small countries provided by IEA only at an aggregate level, such as "Other Africa" and "Other Asia", are disaggregated to CEDS countries using historical CO_2 emissions data from the Carbon Dioxide Information Analysis Center (CDIAC) (Andres et al., 2012; Boden et al., 1995).

L170: Is the BP data freely available?

Yes. BP data is publically available online. The following text has been changed for clarification

IEA energy statistics were extended to 2014 using BP Statistical Review of World Energy (BP,

2015), **which is freely available online** and provides annual updates of country energy

L180: Please provide a reference for the MEIC inventory.

The MEIC citation has been added. Thank you.

L195-196: This statement conveys ambiguity in the use of population data for generating emission trends. Please clarify.

This text has been changed to:

"While non-combustion emissions use population as an "activity driver" in calculations, emissions trends are determined by a combination of EDGAR and country level inventories. Final emissions estimates, therefore, reflect recent emissions inventories where these are available, rather than population trends."

L214: I feel that this equation can be moved up near the beginning of section 2.1 as it describes clearly how activity data and emissions factors are combined to obtain emissions.

Thank you for your suggestion. We've kept the formal equation where it is to avoid restructuring a too much text, but added the simple "emissions = driver x emission factor" phrase to section 2.1.

P9L310-311: To clarify, is the "value" of the scaling factor limited to greater than 1/100 and less than 100? If so, please rephrase the sentence.

Yes, that is correct. Thank you for this comment. The following change has been made in the manuscript:

Calculated scaling factors are **limited to values between 1/100 and 100. Scaling factors outside this range** may result from…

L344: Replace does with do.

This change has been made, thank you.

L396-399: Specify that the discussion in paragraph is pertinent to soil NH3 and NOx emissions.

"Emissions from mineral and manure emissions…" has been changed to "NH_3 and NO_X emissions from mineral and manure are often…"

L413: Which CEDS sectors are the authors referring to here? The 55 working sectors, the 16 intermediate sector or the 9 aggregated sectors?

By "in most sectors" we mean, for most of the data, which could mean any sector aggregation. To avoid confusion "Proxy data used for gridding in most CEDS sectors are primarily gridded emissions …" has been changed to "Proxy data used for gridding are primarily gridded emissions from…" Thank you for this comment

L414: Please clarify what sector (of the 9 aggregated) is the flaring emission relevant for.

Flaring emissions are one of the intermediate gridding sectors within the energy sector for final gridding. Final gridding sectors have been added to table 6 for clarification.

P15, Figure 2: The figure caption says that aviation emissions are not included but the color bar shows "Air" as an option. Please clarify

Even though "Air" was in the legend, the figure did not show any emissions, as they were not included in the graph. The Air sector has been removed from the legend in these figures for clarity.

P16, Figure 3: The label "International" to describe international aviation and shipping is misleading. Suggest replacing it with Air_ship (or some combination of air and ship) so that it is clear the authors are referring to combined aviation and shipping emissions.

The region "International" has been changed to "International Air-Ship" throughout the paper.

L451: Please clarify "anthropogenic emissions" from which inventory are being referred to here. Are the CEDS anthropogenic emissions 20-30% of the total global emissions for BC, OC, NMVOC, and CO?

The following paragraph has been rearranged to read:

"In 1850, the earliest year in which most existing data sets provide estimates, anthropogenic emissions are dominated by residential sector cooking and heating and therefore products of incomplete combustion for BC, OC, CO, and NMVOC. In 1850, anthropogenic emissions (sectors included in this inventory), make up approximately 20 – 30% of total global emissions (which also include grassland and forest burning, estimated by Lamarque et al. (2010)) for BC, OC, NMVOC, and CO but only 3% of global NO_X emissions."

L459: replace "in 1950" with "post 1950"

This change has been made.

L460: Insert a reference to Figure 3 at the end of the sentence.

This change has been made.

L480: Can the authors postulate any specific reasons for the flat residential biomass emissions in latin America despite a growing rural population, and flatter China emissions than rural population after 1990?

The following text was added:

"While rural population in China continually grows, residential biomass use flattens in 1990 as both the share of urban population in China increases and rural residential per capita biomass use

decreases."

L496: replace 'species of emissions" with "species emissions"

This change has been made

L506: Please refer to a figure to support the statement "Global CO emissions flatten".

The following text has been added to the sentence: "… shown in Figure 2 and in more detail in the Supplemental figures and tables."

L514-515: Please clarify the sentence: "offset by international shipping emissions grow then decrease…"

Thank you for pointing out this poorly phrased sentence. This sentence has been changed to:

"Global NO_X emissions rise then flatten around 2008. The growth in industrial emissions after 2000 is offset in 2007 by the decrease in international shipping emissions, while global emissions in other sectors stay flat."

L516: Is it possible that the decline in North American NOx emissions is driven by the decreases in US NOx emissions in response to the NOx control regulations implemented in the US (NOx SIP call). This is fairly well documented and literature should be referenced here as this lends confidence to the trends in NOx emissions derived from CEDS.

Thank you. A reference was added.

L521: A reference is needed for "more stringent emission standards for power plants"

Thank you. A reference was added.

L554-L559: Please refer to a specific figure in the Figures and Tables Supplement for this comparison (e.g., Figure S40). I would also suggest doing the same for other species in the paragraphs below as it is cumbersome to sift through the many plots.

Thanks. Specific references to supplemental figures have been added strategically in the results sections of the manuscript.

Section 3.4: It would be very helpful to have a table with published level of uncertainties in emissions for each species (CO2, SO2, CO, NOx, NMVOC, BC, OC) and specific sectors. Much of the information is contained in this section and can be pulled into a summary table that will come in handy when uncertainties in CEDS emissions are determined.

While we agree this would be useful, we will refer the reader to the literature summary in IPCC AR5 for now (we're not aware of a more up to date general summary) as more significant effort to collect uncertainty estimates will need to wait for future work.

L622: This sentence can be rephrased to " Emissions uncertainties for CO, NOx, and NMVOCs

typically lie between those of carbonaceous aerosols...."

This change has been made. Thanks.

L626-627: Hassler et al (2016) should also be cited here.

This citation has been added.

L637-639: Paulot et al can be cited here as an example of detailed modeling of agricultural NH3 emissions.

This citation has been added.

Section 5. The ultimate test of an emission inventory is comparison of species concentrations simulated by a model driven by an inventory against observations (e.g., Parrish et al., 2014; Hassler et al., 2016). If the model is able to capture the distribution and trends then the said inventory is considered to represent the real conditions well. I think a case could be made for better coordination between modelers and emission inventory developers so that a two-way interaction can help improve both models and emissions inventories.

We agree in general, although note that models are not necessary in all cases: Hassler et al., for example, use observations directly. There are many complications of course: models are imperfect or incomplete, observations are often not available at the same scale as model results, and inventories are often not available at scale of observations (e.g. Wang et al. doi/10.1073/pnas.1318763111).

We have added a comment on this in the future work section.

An outline of long-term plans for the CEDS database is needed in the summary section to build confidence in its sustainability. Modelers would like to know if they can rely on the CEDS system working even after CMIP6. What are the plans for maintenance of the back-end software, frequency of updates to the input data and for maintaining funding for CEDS?

Thanks. The following text has been added to the manuscript detailing future plans for the System and community engagement.

"The CEDS data system, including R code and all input data other than the IEA energy balances, is being prepared for public release in fall 2017 through the gitHub collaboration website. This will facilitate community comment, and direct contributions to improving these emissions data. The next data release is planned for Fall 2017, which will extend the time series to 2016 and correct, to the extent possible, any known issues with the dataset. We aim to continue annual updates in subsequent years."

References:

Paulot, F., D. J. Jacob, R. W. Pinder, J. O. Bash, K. Travis, and D. K. Henze (2014), Ammonia

emissions in the United States, European Union, and China derived by high- resolution inversion of ammonium wet deposition data: Interpretation with a new agri- cultural emissions inventory (MASAGE_NH3), J. Geophys. Res. Atmos., 119, 4343– 4364, doi:10.1002/2013JD021130.

Hassler, B., et al. (2016), Analysis of long-term observations of NOx and CO in megac- ities and application to constraining emissions inventories, Geophys. Res. Lett., 43, 9920–9930, doi:10.1002/2016GL069894.

Historical (1750 – 2014) anthropogenic emissions of reactive gases and aerosols from the Community Emission Data System (CEDS)

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Abstract. We present a new data set of annual historical (1750 - 2014) anthropogenic chemically reactive gases (CO, CH_4, NH_3, NO_X, SO_2, NMVOC), carbonaceous aerosols (BC and OC), and CO_2 developed with the Community Emissions Database System (CEDS). We improve upon existing inventories with a more consistent and reproducible methodology applied to all emissions species, updated emission factors, and recent estimates through 2014. The data system relies on existing energy consumption data sets and regional and country-specific inventories to produce trends over recent decades. All emissions species are consistently estimated using the same activity data over all time periods. Emissions are provided on an annual basis at the level of country and sector and gridded with monthly seasonality. These estimates are comparable to, but generally slightly higher than, existing global inventories. Emissions over the most recent years are more uncertain, particularly in low- and middle-income regions where country-specific emission inventories are less available. Future work will involve refining and updating these emission estimates, estimating emissions uncertainty, and publication of the system as open source software.

1

1 Introduction

Anthropogenic emissions of reactive gases, aerosols, and aerosol precursor compounds have substantially changed atmospheric composition and associated fluxes to land and ocean surfaces. As a result, increased particulate and tropospheric ozone concentrations since pre-industrial times have altered radiative balances of the atmosphere, increased human mortality and morbidity, and impacted terrestrial and aquatic ecosystems. Central to studying these effects are historical trends of emissions. Historical emissions data and consistent emissions time series are especially important for Earth Systems Models (ESMs) and atmospheric chemistry and transport models, which use emissions time series as key model inputs; Integrated Assessment Models (IAMs), which use recent emissions data as a starting point for future emissions scenarios; and to inform management decisions.

Despite their wide use in research and policy communities, there are a number of limitations to current inventory data sets. Emissions data from country and regional specific inventories vary in methodology, level of detail, sectoral coverage, and consistency over time and space. Existing global inventories do not always provide comprehensive documentation for assumptions and methods and few contain uncertainty estimates.

Several global emissions inventories have been used in global research and modeling. The Emissions Database for Global Atmospheric Research (EDGAR) is a widely used historical global emissions data set. It provides an independent estimate of historical greenhouse gas (GHG) and pollutant emissions by country, sector, and spatial grid (0.1 x 0.1 degree) from 1970 – 2010 (Crippa et al., 2016; EC-JRC/PBL, 2016), with GHG emission estimates for more recent years. The most recent set of modeling exercises by the Task Force on Hemispheric Transport of Air Pollutants (HTAP) uses a gridded emissions data set, HTAP v2 (Janssens-Maenhout et al., 2015), that merged EDGAR with regional and country-level gridded emissions data for 2008 and 2010. The GAINS (Greenhouse gas - Air pollution Interactions and Synergies) model (Amann et al., 2011) has been used to produce regional and global emission estimates for several recent years (1990- 2010; in five year intervals) together with projections to 2020 and beyond (Amann et al., 2013; Cofala et al., 2007; Klimont et al., 2009). These have been developed with substantial consultation with national experts, especially for Europe and Asia (Amann et al., 2008, 2015; Purohit et al., 2010; Sharma et al., 2015; Wang et al., 2014; Zhang et al., 2007; Zhao et al., 2013a). The newly developed ECLIPSE emission sets include several extensions and updates in the GAINS model and are also available in a gridded form (Klimont et al., 2017a) and have been used in a number of recent modeling exercises (Eckhardt et al., 2015; IEA, 2016b; Rao et al., 2016; Stohl et al., 2015).

Lamarque et al. (2010) developed a historical data set for the Coupled Model Intercomparison Project Phase 5 (CMIP5), which includes global, gridded estimates of anthropogenic and open burning emissions from 1850 – 2000 at 10 year intervals, referred to here as the CMIP5 historical data. It was a compilation of "best available estimates" from many sources including black carbon (BC) and organic carbon (OC) from Bond et al. (2007) and EDGAR-HYDE (van Aardenne et al., 2001) which provides global anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOC), sulfur dioxide (SO_2) and ammonia (NH_3) from 1890 to 1990 every 10 years at 1 x 1 degree grids; RETRO (Schultz and Sebastian, 2007) which estimated global emissions from 1960 to 2000; and emissions reported by, largely, Organization for Economic Co-operation and Development (OECD) countries over recent years. While this data set was an

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improvement upon the country and regional specific inventories mentioned above, it lacks uncertainty estimates and reproducibility, has limited temporal resolution (10 year estimates to 2000), and does not have consistent methods across time and emission species. There are many existing inventories of various scope, coverage, and quality; however, no existing data set meets all the growing needs of the modeling community.

The Lamarque et al. year 2000 data were also used as the starting point for the Representative Concentration Pathways (RCP) scenarios spanning 2000 to 2100 (van Vuuren et al., 2011) and is, therefore, also known at the RCP historical data.

This paper describes the general methodology and results for an updated global historical emissions data set that has been designed to meet the needs of the global atmospheric modeling community and other researchers for consistent long-term emission trends. The methodology was designed to produce annual estimates, be similar to country-level inventories where available, be complete and plausible, and use a consistent methodology over time with the same underlying driver data (e.g., fuel consumption). The data set described here provides a sectoral and gridded historical inventory of climate-relevant anthropogenic GHGs, reactive gases, and aerosols for use in the Coupled Model Intercomparison Project Phase 6 (CMIP6). It does not include agricultural waste burning, which is included in van Marle et al. (van Marle et al., 2017). The May 2017 CEDS data release (CEDS-v2017-05-18), which corrected mistakes in previous gridded data releases (see Appendix A2), includes estimates of SO_2, NO_x, NH_3, carbon monoxide (CO), BC, OC, NMVOC, CO_2, and CH_4 (CH_4 estimates from 1970 – 2014). This data set was created using the Community Emissions Database System (CEDS), which will be released as open-source software. Updated information on the system and its release status can be found at http://www.globalchange.umd.edu/ceds/.

An overview of the methodology and data sources are provided in Sect. 2 while further details on the methodology and data sources are included in the Supplementary Information (SI), outlined in Sect. 2.7. Section 3 compares this data set to existing inventories and Sect. 4 details future work involving this data set and system.

2   Data and methodology

2.1   Methodological overview

CEDS uses existing emissions inventories, emissions factors, and activity/driver data to estimate annual country, sector, and fuel specific emissions over time in several major phases (data system schematic shown in Figure 1):

1) data are collected and processed into a consistent format and timescale (detailed in Sect. 2.2 and throughout paper),

2) default emissions from 1960/1971 (1960 for most OECD countries and 1971 for all others) to 2014 are estimated using driver and emission factor data (Emissions = Driver × Emission Factors) (Sect. 2.2),

3) default estimates are scaled to match existing emissions inventories where available, complete, and plausible (Sect. 2.4),

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Deleted: in July 2016 (CEDS-v2016-07-26) were released in summer 2016 through the Earth System Grid Federation (ESGF) systemª (links provided in Sect. A1) and

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185   4)   scaled emissions estimates are extended back to 1750 (Sect. 2.5) to produce final aggregate emissions by country, fuel and sector,

    5)   emissions are summarized to produce data for release and analysis and

    6)   gridded emissions with monthly seasonality and VOC speciation are produced from aggregate estimates using spatial proxy data (Sect. 2.6).
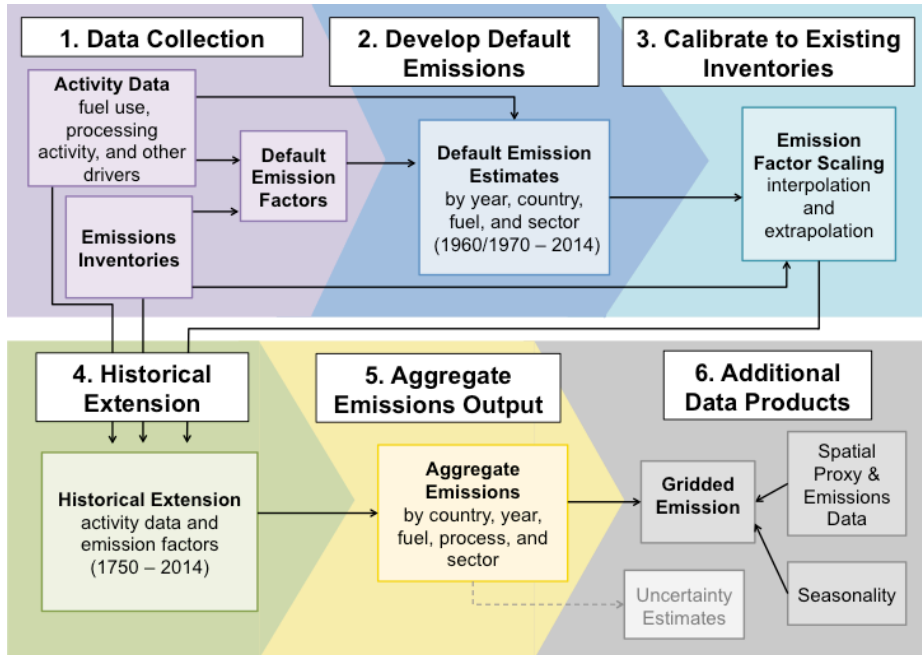
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Figure 1: System Summary. Key steps in calculation are: 1) Collect and process activity, emissions factors, and emissions data 2) Develop default emissions estimates 3) Calibrate default estimates to existing inventories 4) Extend present day emission to historical time periods 5) Summarize emissions outputs 6) Produce data products including gridded emissions and uncertainty estimates.

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Rather than producing independent estimates, this methodology relies on matching default estimates to reliable, existing emissions inventories (emission scaling) and extending those values to historical years (historical extension) to produce a consistent historical time series. While previous work (Lamarque et al., 2010) combined different data sets then smoothed over
200 discontinuities, CEDS produces historical trends by extending the individual components (driver data and emissions factors) separately to estimate emission trends. This method captures trends in fuel use, technology, and emissions controls over time. Estimating emissions from drivers and emission factor components also allows the system to estimate emissions in recent years, using extrapolated emission factors and quickly released fuel use data, where energy statistics and
205 emission inventories are not yet available.

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CEDS estimates emissions for 221 regions (and a global region for international shipping and aircraft), 8 fuels, and 55 working sectors, summarized in Table 1. "Regions" refers to countries, regions, territories, or islands and are listed, along with mapping to summary regions and ISO codes in the supplemental files; they will henceforth be referred to as "countries". CEDS working sectors (sectors 1A1-1A5) for combustion emissions follow the International Energy Agency (IEA) energy statistics sector definitions (Table A1). The IEA energy statistics are annually updated and the most comprehensive global energy statistics available, so this choice allows for maximal use of this data. Non-combustion emissions sectors (sectors 1A1bc and 1B-7) are drawn from EDGAR and generally follow EDGAR definitions (Table A2). Sector names were derived from Intergovernmental Panel on Climate Change (IPCC) reporting categories under the 1996 guidelines and Nomenclature for Reporting (NFR) 14 together with a short descriptive name. Note that CEDS data do not include open burning, e.g. forest and grassland fires, and agricultural waste burning on fields, which was developed by van Marle et al (2017). Tables providing more detailed information on these mappings, which define the CEDS sectors and fuels, are provided in Sect. A3. We note that, while agriculture sectors include a large variety of activities, in practice in the current CEDS system these sectors largely represent NH_3 and NO_X emissions from fertilizer application (under 3D_Soil-emissions) and manure management, due to the focus in the current CEDS system on air-pollutant emissions.

In order to produce timely emissions estimates for CMIP6, several CEDS emission sectors in this version of the system aggregate somewhat disparate processes to reduce the need for the development of detailed driver and emission factor information. For example, process emissions from the production of iron and steel, aluminum, and other non-ferrous metals are grouped together as an aggregate as 2C_Metal-production sector. Similarly, emissions from a variety of processes are reported in 2B_Chemical-industry. Also, the 1A1bc_Other-tranformation sector includes emissions from combustion related activities in energy transformation processes including coal and coke production, charcoal production and petroleum refining, but are combined in one working sector (see Sec 2.3.2). Greater disaggregation for these sectors would improve these estimates, but will require additional effort, described in Sect.5 Limitations and Future work.

The core outputs of the CEDS system are country-level emissions aggregated to the CEDS sector level. Emissions by fuel and by detailed CEDS sector are also documented within the system for analysis, although these are not released due to data confidentiality issues. Emissions are further aggregated and processed to provide gridded emissions data with monthly seasonality, detailed in Sect. 2.6.

We note that the CEDS system does not reduce the need for more detailed inventory estimates. For example, CEDS does not include a representation of vehicle fleet turnover and emission control degradation (*e.g.* the effectiveness of catalytic converters over time) or multiple fuel combustion technologies that are included in more detailed inventories. The purpose of this system, as described further below, is to build on a combination of global emission estimation frameworks such as GAINS and EDGAR, combined with country-level inventories, to produce reproducible, consistent emissions trends over time, space, and emissions species.

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260 **Table 1 CEDS working sectors and fuels (CEDS v2016-07-26)**

CEDS Working Sectors		
Energy Production	1A2g_Ind-Comb-other	**RCO**
1A1a_Electricity-public	2A1_Cement-production	1A4a_Commercial-institutional
1A1a_Electricity-autoproducer	2A2_Lime-production	1A4b_Residential
1A1a_Heat-production	2Ax_Other-minerals	1A4c_Agriculture-forestry-fishing
1A1bc_Other-transformation	2B_Chemical-industry	1A5_Other-unspecified
1B1_Fugitive-solid-fuels	2C_Metal-production	**Agriculture**
1B2_Fugitive-petr-and-gas	2D_Other-product-use	3B_Manure-management
1B2d_Fugitive-other-energy	2D_Paint-application	3D_Soil-emissions
7A_Fossil-fuel-fires	2D_Chemical-products-manufacture-processing	3I_Agriculture-other
Industry		3D_Rice-Cultivation
1A2a_Ind-Comb-Iron-steel	2H_Pulp-and-paper-food-beverage-wood	3E_Enteric-fermentation
1A2b_Ind-Comb-Non-ferrous-metals		**Waste**
1A2c_Ind-Comb-Chemicals	2D_Degreasing-Cleaning	5A_Solid-waste-disposal
1A2d_Ind-Comb-Pulp-paper	**Transportation**	5E_Other-waste-handling
1A2e_Ind-Comb-Food-tobacco	1A3ai_International-aviation	5C_Waste-combustion
1A2f_Ind-Comb-Non-metalic-minerals	1A3aii_Domestic-aviation	5D_Wastewater-handling
1A2g_Ind-Comb-Construction	1A3b_Road	
1A2g_Ind-Comb-transpequip	1A3c_Rail	
1A2g_Ind-Comb-machinery	1A3di_International-shipping	6A_Other-in-total
1A2g_Ind-Comb-mining-quarrying	1A3di_Oil_tanker_loading	6B_Other-not-in-total
1A2g_Ind-Comb-wood-products	1A3dii_Domestic-navigation	
1A2g_Ind-Comb-textile-leather	1A3eii_Other-transp	

CEDS Fuels		
Hard Coal	Light Oil	Natural Gas
Brown Coal	Diesel Oil	Biomass
Coal Coke	Heavy Oil	

2.2 Activity data

Trends of energy consumption and other driver (activity) data are key inputs for estimating emissions. When choosing data to use in this system, priority was given to consistent trends over 265 time rather than detailed data that might only be available for a limited set of countries or time-span.

2.2.1 Energy data

Energy consumption data are used as drivers for emissions from fuel combustion. Core energy data for 1960 - 2013 are the International Energy Agency (IEA) energy statistics, which provides 270 energy production and consumption estimates by detailed country, fuel, and sector from 1960 – 2013 for most OECD countries and 1971 – 2013 for non-OECD countries (IEA, 2015). While most data sources used in CEDS are open source, CEDS currently requires purchase of this proprietary data set. IEA data are provided at finer fuel and sector level so data are often aggregated to CEDS sectors and fuels. Mapping of IEA products to CEDS fuels is available in 275 Sect. A3. Data for a number of small countries are provided by IEA only at an aggregate level, such as "Other Africa" and "Other Asia", are disaggregated to CEDS countries using historical CO_2 emissions data from the Carbon Dioxide Information Analysis Center (CDIAC) (Andres et al., 2012; Boden et al., 1995). Sectoral splits for Former Soviet Union (FSU) countries are smoothed over time to account for changes in reporting methodologies during the transition to 280 independent countries (see SI).

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IEA energy statistics were extended to 2014 using BP Statistical Review of World Energy (BP, 2015), which is freely available online and provides annual updates of country energy totals by aggregate fuel (oil, gas and coal). BP trends for aggregate fuel consumption from 2013 to 2014

305 were applied to all CEDS sectors in the corresponding CEDS fuel estimates to extrapolate to 2014 energy estimates by sector and fuel from 2012 IEA values.

In a few cases, IEA energy data were adjusted to either smooth over discontinuities or to better match newer information. For international shipping, where a number of studies have concluded that IEA reported consumption is incomplete (Corbett et al., 1999; Endresen et al., 2007; Eyring

310 et al., 2010), we have added additional fuel consumption so that total consumption matches bottom-up estimates from International Maritime Organization (IMO) (2014). For China, fuel consumption appears to be underestimated in national statistics (Guan et al., 2012; Liu et al., 2015b), so coal and petroleum consumption were adjusted to match the sum of provincial estimates as used in the MEIC inventory (Multi-resolution Emissions Inventory for China) (Li et

315 al., 2017) used to calibrate CEDS emission estimates. Several other changes were made, such as what appears to be spurious brown coal consumption over 1971-1984 in the IEA Other Asia region and a spike in agricultural diesel consumption in Canada in 1984. All such changes are documented in CEDS source code, input files, and supplementary information provided with this article.

320 Residential biomass was estimated by merging IEA energy statistics and Fernandes et al. (2007) to produce residential biomass estimates by country and fuel type over 1850 - 2013. Residential biomass data were reconstructed with the assumption that sudden drops in biomass consumption going back in time are due to data gaps, rather than sudden energy consumption changes. Both IEA and Fernades et al. values were reconstructed to maintain smooth per capita (based on rural

325 population) residential biomass use over time.

Detail on methods and assumption for energy consumption estimates are available in the Data and Assumption Supplement (SI-Text) Sect. 3.

2.2.2 Population and other data

Consistent historical time trends are prioritized for activity driver data. For non-combustion

330 sectors population is generally used as an activity driver. United Nations (UN) Population data (UN, 2014, 2015) is used for 1950 – 2014, supplemented from 1960 – 2014 with World Bank population statistics (The World Bank, 2016). This series was merged with HYDE historical population data (Klein Goldewijk et al., 2010). More detail is available in SI-Text Sect. 2.1.

In this data version, population is used as the non-combustion emissions driver for all but three

335 sectors. 5C_Waste-combustion, which includes industrial, municipal, and open waste burning, is driven by pulp and paper consumption, derived from Food and Agriculture Organization of the UN (FAO) Forestry Statistics (FAOSTAT, 2015). FAO statistics converted to per capita values were smoothed and linearly extrapolated backward in time. 1B2_Fugitive-petr-and-gas, which are fugitive and flaring emissions from production of liquid and gaseous fuels together with oil

340 refining, is driven by a composite variable that combines domestic oil and gas production with refinery inputs, derived from IEA Energy Statistics. This same driver is also used for 1B2d_Fugitive-other-energy. More detail is available in SI-Text Sect. 2.5. While non-combustion emissions use population as an "activity driver" in calculations, emissions trends are generally determined by a combination of EDGAR and country level inventories. Final

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355 emissions estimates, therefore, reflect recent emissions inventories where these are available, rather than population trends.

2.3 Default estimates

Significant effort is devoted to creating reliable default emissions estimates, including abatement measures, to serve as a starting point for scaling to match country-level inventories (Sect. 2.4)
360 and historical extension back to 1750 (Sect. 2.5). While most default estimates do not explicitly appear in the final data set as they are altered to match inventories (Sect. 2.4), some are not altered because inventories are not available for all regions, sectors, and species. The method for calculating default emission factors varies by sectors and regions depending on available data.

Default emissions estimates (box 2 in Figure 1), are calculated using 3 types of data (box 1 in
365 Figure 1): activity data (usually energy consumption or population), emissions inventories, and emissions factors, according to Eq. (1).

$$E_{em}^{c,s,f,t} = A^{c,s,f,t} \times EF_{em}^{c,s,f,t}$$

(1)

370 Where E is total emissions, A is activity or driver, EF is emissions factor, em is emission species, c is country, s is sector, f is fuel (where applicable), and t is year.

In general, default emissions for fuel combustion (sectors 1A in Table 1) are estimated from emission factors and activity drivers (energy consumption), while estimates of non-combustion
375 emissions (sectors 1B – 7A and 1A1bc) are taken from a relevant inventory and the "implied emissions factor" is inferred from total emissions and activity drivers.

2.3.1 Default fuel combustion emissions

Combustion sector emissions are estimated from energy consumption estimates (Sect. 2.2), and emissions factors according to Eq. (1). Default emission factors for the combustion of fuels are
380 derived from existing global data sets that detail emissions and energy consumption by sector and fuel, using Eq. (2):

$$EF_{em}^{c,s,f,t} = \frac{E_{em}^{c,s,f,t}}{A^{c,s,f,t}}$$

(2)

Where EF is default emission factor, E is total emissions as reported by other inventories, A is
385 activity data, measured in energy consumption as reported by inventories, em is emission species, c is country, s is sector, f is fuel (where applicable), and t is year.

The main data sets used to derive emission factors are shown in Table 2. Default emission factors for NO_X, NMVOC, CO, and CH_4 are estimated from the global implementation of the
390 GAINS model as released for the Energy Modeling Forum 30 project (https://emf.stanford.edu/projects/emf-30-short-lived-climate-forcers-air-quality) (Klimont et al.,

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2017a, 2017; Stohl et al., 2015). BC and OC emission factors from 1850 – 2000 are estimated from the latest version of the Speciated Pollutant Emission Wizard (SPEW) (Bond et al., 2007).

395 Emission factors for CO_2 emissions for coal and natural gas combustion are taken from CDIAC (Andres et al., 2012; Boden et al., 1995), with an additional coal mass balance check, as further described in SI-Text Sect. 5.4. For coal in China a lower oxidation fraction of 0.96 was assumed, see discussion in the SI-Text (Liu et al., 2015b). Because CEDS models liquid fuel emissions by fuel grade (light, medium, heavy), we use fuel-specific emission factors for liquid fuels also
400 described in SI-Text Sect. 5.4.

Emission data are aggregated by sector and fuel to match CEDS sectors, while calculated emission factors from more aggregate data sets are applied to multiple CEDS sectors, fuels, or countries. When incomplete time series are available, emission factors are generally assumed constant back to 1970 linearly interpolated between data points, and extended forward to 2014
405 using trends from GAINS to produce a complete times series of default emission factors. Many of these interpolated and extended values are later scaled to match county inventories (Sect. 2.4).

Most of the default emission factors are derived from sources that account for technology efficiencies and mitigation controls over time, but some are estimated directly from fuel properties (e.g., fuel sulfur content for SO_2 emissions). A control percentage is used to adjust the
410 emission factor in these cases. In the data reported here the control percentage is primarily used in SO_2 calculations (see SI-Text Sect. 5.1) where the base emission factor is derived directly from fuel properties; however, this functionality is available when needed for other emission species. In most of these cases emissions are later scaled to match inventory data.

415 **Table 2 Data Sources used to estimate default emissions factors for fuel combustion and default emissions from non-combustion sectors**

Source Sector	Emission Species	Data Source
Fuel Combustion (1A)	NO_X, NMVOC, CO, CH_4	GAINS energy use and emissions (Klimont et al., 2017a; Stohl et al., 2015).
	BC, OC	SPEW energy use and emissions (Bond et al., 2007)
	SO_2	(Europe) GAINS sulfur content and ash retention (Amann et al., 2015; IIASA, 2014a, 2014b). Smith et al. (2011) and additional sources for other regions (SI-Text 5.1)
	NH_3	US NEI energy use and emissions (US EPA, 2013)
	CO_2	CDIAC (Boden et al., 2016) and additional data sources
Fugitive Petroleum and Gas (1B)	All	EDGAR emissions(EC-JRC/PBL, 2016), ECLIPSE V5a (Stohl et al., 2015)
Cement (2A1)	CO_2	CDIAC (Boden et al., 2016)
Agriculture Sectors (3)	CH_4	For Sectors 3B_Manure-management, 3B_Soil-emissions, and 3D_Rice-Cultivation: FAOSTAT (FAO, 2016) all others: EDGAR emissions (EC-JRC/PBL, 2016)
	Other	EDGAR emissions (EC-JRC/PBL, 2016)

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Waste Combustion (5C)	All	(Akagi et al., 2011; Andreae and Merlet, 2001; Wiedinmyer et al., 2014) (SI-Text Sect. 6.3)
Waste Water Treatment (5D)	NH$_3$	CEDS estimate of NH$_3$ from human waste (SI-Text Sect. 6.4)
Other Non-Combustion (2A – 7A)	SO$_2$	EDGAR, (Smith et al., 2011) & other sources (SI-Text Sect. 6.5)
	Other	EDGAR emissions (EC-JRC/PBL, 2016)

2.3.2 Default non-combustion emissions

Default non-combustion emissions, are generally taken from existing emissions inventories, primarily EDGAR (EC-JRC/PBL, 2016) and some additional sources for specific sectors detailed in Table 2. Default emissions from sectors not specifically called out in Table 2 or the text below are taken from EDGAR (EC-JRC/PBL, 2016). Other data sources and detailed methods are explained in the SI-Text Sect. 6. For detailed sector definitions refer to Sect. A3.

When complete trends of emissions estimates are not available, they are extended in a similar manner as combustion emissions: emission factors are inferred using Eq. (2) and (with few exceptions) using population as an activity driver; emission factors (e.g. per-capita emissions) are linearly interpolated between data points and extended forward and back to 1970 and 2014 to create a complete trend of default emission factors; and default emissions estimates are calculated using Eq. (1).

For this data set, all non-combustion sectors (except for 5C_Waste-combustion) use population as the activity driver since this provides a continuous historical time series to be used where interpolations were needed. In practice, since EDGAR is generally used for default non-combustion data source, we are relying on EDGAR trends by country to extend emissions data beyond years where additional inventory information does not exist (with exceptions as noted in Table 2). Sector uses pulp and paper consumption, detailed in Sect. 2.2; while the waste combustion sector, which incorporates solid waste disposal (incineration) and residential waste combustion, and is the product of combustion, in this system it is methodologically treated as a non-combustion sector.

We note that, while emissions from sector 1A1bc_Other_tranformation are also due to fuel combustion, due to the complexity of the processes included, this sector is treated as a non-combustion sector in CEDS in terms of methodology. This means that fuel is not used as an activity driver and that default emissions for this sector are taken from SPEW for BC and OC and EDGAR for other emissions. The major emission processes in this sector include coal coke production, oil refining, and charcoal production. A mass balance calculation for SO$_2$ and CO$_2$ focusing on coal transformation was also conducted to assure that these specific emissions were not underestimated, particularly for periods up to the mid 20th century (SI-Text Sect. 5.4, 6.5.2, and 8.3.2).

During the process of emissions scaling we found that default emissions were sometimes 1-2 orders of magnitude different from emissions reported in national inventories. This is not surprising, since non-combustion emissions can be highly dependent on local conditions, technology performance, and there are also often issues of incompleteness of inventories. In these cases, we implemented a process whereby default non-combustion emissions were taken

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directly from national inventories, and gap-filled and trended over time using EDGAR estimates. These were largely fugitive and flaring emissions (1B) for SO_2; soil(3D), manure(3B), and waste water(5D) emissions for NH_3; and non-combustion emissions for NMVOCs, typically associated with solvent use.

2.4 Scaling emissions

CEDS uses a "mosaic" strategy to scale default emissions estimates to authoritative country-level inventories when available. The goal of the scaling process is to match CEDS emissions estimates to comparable inventories while retaining the fuel and sector detail of the CEDS estimates. The scaling process modifies CEDS default emissions and emission factors, but activity estimates remain the same.

A set of scaling sectors is defined for each inventory so that CEDS and inventory sectors overlap. These sectors are chosen to be broad, even when more inventory detail is available, because it is often unclear if sector definitions and boundaries are comparable between data sets. For example, many inventories do not consistently break out industry auto-producer electricity from other industrial combustion, so they are combined together for scaling. Additionally, underlying driver data in inventories and CEDS may not match. Scaling detailed sectors that were calculated using different energy consumption estimates would yield unrealistic scaled emission factors at a detailed sector level. One example is off-road emissions; while often estimated in country inventories, energy consumption data at this level is not consistently available from the IEA energy statistics, so these emissions are combined into broader sector groupings, depending on the sector categories available in a specific inventory.

The first step in this process is to aggregate CEDS emissions and inventory emissions to common scaling sectors, then scaling factors are calculated with Eq. (3). Scaling factors represent the ratio between CEDS default estimates and scaling inventory estimates by scaling sector and provide a means for matching CEDS default estimates to scaling inventories.

$$SF_{em}^{c,ss,t} = \frac{Inv_{em}^{c,ss,t}}{CEDS_{em}^{c,ss,t}}$$

(3)

Where SF is scaling factor, Inv is the inventory emissions estimate, CEDS is the CEDS emissions estimate, em is emission species, c is country, ss is aggregate scaling sector (unique to inventory), and t is year.

For each inventory, scaling factors are calculated for years when inventory data are available. Calculated scaling factors are limited to values between 1/100 and 100. Scaling factors outside this range may result from discontinuities or misreporting in inventory data; imperfect scaling maps between CEDS sectors, inventory sectors, and scaling sectors; or default CEDS emissions estimates that are drastically different than reported inventories. Many of these cases were resolved by using the detailed inventory data as default emissions data, as noted above in Sect 2.3.2. Where inventory data are not available over a portion of the specified scaling timeframe, remaining scaling factors are extended, interpolated between to provide a continuous trend. Scaling factors are applied to corresponding CEDS default emissions estimates and default emission factors to produce a set of scaled emissions components (total emissions and emission

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factors, together with activity drivers, which are not changed), which are used in the historical extension (Sect. 2.5). Using scaling factors retains the sector and fuel level detail of CEDS default emissions estimates, while matching total values to authoritative emissions inventories.

We use a sequential methodology in which CEDS values are generally first scaled to EDGAR (EC-JRC/PBL, 2016) for most emission species, then national inventories, where available. Final CEDS results, over the period these inventories were available, match the last inventory scaled. SO_2, CH_4, BC, and OC are not scaled to EDGAR values. For all pollutant species other than BC and OC, estimates are then scaled to match country-level emissions estimates. These are available for most of Europe through European Monitoring and Evaluation Programme (EMEP) for European countries post 1980 (EMEP, 2016); the United Nations Framework Convention on Climate Change (UNFCCC) GHG data for Belarus, Greece and New Zealand (UNFCCC, 2015) post 1990; an updated version of Regional Emissions Inventory in Asia (REAS) for Japan (Kurokawa et al., 2013a); Multi-resolution Emissions Inventory for China (MEIC) for China (Li et al., 2017); and others detailed in Table 3. BC and OC emissions estimates are entirely from default estimates calculated using predominantly SPEW data. While BC inventory estimates were available in a few cases, OC estimates were less available, so we have retained the consistent BC and OC estimates from SPEW for all countries. CH_4 emissions estimates are scaled to match to the following inventories: EDGAR 4.2 (EC-JRC/PBL, 2012), UNFCCC submissions UNFCCC, 2015) for most "Annex I" countries, and the US GHG inventory (US EPA, 2012b) for the United States.

The scaling process was designed to allow for exceptions when there are known discontinuities in inventory data or when the default scaling options resulted in large discontinuities. For example, Former Soviet Union countries were only scaled to match EDGAR and other inventories after 1992 (where energy data becomes more consistent). Romania, for example, was only scaled to match EDGAR in 1992, 2000, and 2010 to avoid discontinuities. For the most part, these exceptions occur for countries with rather limited penetration of control measures or only low efficiency controls. Regions with more stringent emission standards requiring extensive application of high efficiency controls have typically higher quality national inventories, e.g., European Union, North America, and parts of Asia.

Description of the exceptions and assumptions for all scaling inventories, as well as a detailed example of the scaling process is available in SI-Text Sect. 7. Additionally, figures showing stacked area graphs of global emission, by final scaling inventory (or default estimate) are shown in Supplemental Figures and Tables Sect. J. These show the percentage of final global emissions estimates that are scaled to various inventories.

Table 3 Data Sources for Inventory Scaling. All countries scaled to EDGAR, then individual estimates.

Region/ Country	Species	Years	Data Source
All, where available	NO_X, NMVOC, CO, NH_3	1970 - 2008	EDGAR 4.3 (EC-JRC/PBL, 2016)
	CH_4	1970 - 2008	EDGAR 4.2 (EC-JRC/PBL, 2012)

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Europe	SO$_2$, NO$_X$, NMVOC, CO, NH$_3$	1980 - 2012	(EMEP, 2016)
Greece, New Zealand, Belarus	SO$_2$, NO$_X$, NMVOC, CO, CO2	1990 - 2012	(UNFCCC, 2015)
Other Asia	SO$_2$, NO$_X$, NMVOC, CO, CH4	2000 - 2008	REAS 2.1 (Kurokawa et al., 2013a)
Argentina	SO$_2$, NO$_X$, NMVOC, CO	1990 - 1999, 2001 - 2009, 2011	(Argentina UNFCCC Submission, 2016)
Australia	SO$_2$, NO$_X$, NMVOC, CO	2000, 2006, 2012	(Australian Department of the Environment, 2016)
China	SO$_2$, NO$_X$, NMVOC, CO, NH$_3$	2008, 2010, 2012	MEIC (Li et al., 2017)
Canada	SO$_2$, NO$_X$, NMVOC, CO	1985 - 2011	(Environment and Climate Change Canada, 2016; Environment Canada, 2013)
Japan	SO$_2$, NO$_X$, NMVOC, CO, NH$_3$	1960 - 2010	Preliminary update of Kurokawa et al., (2013b)
South Korea	SO$_2$, NO$_X$, NMVOC, CO	1999 - 2012	(South Korea National Institute of Environmental Research, 2016)
Taiwan	SO$_2$, NO$_X$, NMVOC, CO	2003, 2006, 2010	(TEPA, 2016)
USA	SO$_2$, NO$_X$, NMVOC, CO	1970,1975,1980,1985, 1990 - 2014	EPA Trends (US EPA, 2016b)
	NH$_3$	1990 - 2014	
	CO$_2$	1990 - 2014	US EPA, 2016a)
	CH$_4$	1990 - 2014	US GHG Inventory (US EPA, 2012b)

The scaling process operates on sectors where emissions are present in both the CEDS default data and the scaling inventories listed in Table 3. If the scaling inventory does not contain information for a particular sector then the default data are used. This means that some gaps in the scaling inventories are automatically filled by this procedure and, as a result, the CEDS emission totals can be larger than those in the scaling inventory. For example, waste burning and fossil fuel fires are not included in some of the inventories, while these sectors are included in CEDS. In a few cases, specific additional data were added where gaps were known to be present. For example, the CEDS totals for China are slightly larger than the MEIC totals due to both the inclusion of waste burning, but also the addition of SO$_2$ emissions from metal smelting, which are not included in MEIC. Where necessary discontinuities in inventory estimates were eliminated. For the USA, for example, discontinuities were present in the original EPA trends data due to methodological changes, particularly for transportation NO$_x$ and agricultural NH$_3$.

2.5   Pre-1970 emissions extension

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570 Historical emissions and energy data before 1970 generally do not have the same detail as more modern data. In general, we extend activity and emission factors back in time separately, with time and sector specific options to capture changes in technologies, fuel mixes, and activity. This allows for consistent methods across time and sectors, rather than piecing together different sources and smoothing over discontinuities, which was done in previous work (Lamarque et al.,
575 2010). For most emission species and sectors the assumed historical trend in activity data has a large impact on emission trends. Activity for many sectors and fuels, such as fossil liquid and gas fuels, are small or zero by 1900. Some cases where emission factors are known to have changed over time have also been incorporated.

2.5.1 Pre-1970 activity drivers

580 IEA Energy Statistics, which are the foundation for energy estimates in this data set, go back to 1960 at the earliest. Fossil fuels are extended using CDIAC emissions, SPEW energy data, and assumptions about fuel type and sector splits in 1750, 1850, and 1900, detailed in the SI-Text Sect. 8.1. First total fuel use for three aggregate fossil fuel types, coal, oil, and gas, are estimated over 1750 - 1960/1970 for each country using historical national CO_2 estimates from the Carbon
585 Dioxide Information Analysis Center (CDIAC) (Andres et al., 1999; Boden et al., 2016).

For coal only, these extended trends were matched with SPEW estimates of total coal use, which are a composite of UN data (UN, 2016) and Andres et al., (1999). This resulted in a more accurate extension for a number of key countries. SPEW estimates at every 5 years were interpolated to annual values using CDIAC CO2 time series, resulting in an annual time series.

590 For coal and petroleum, aggregate fuel use was disaggregated into specific fuel types (e.g., brown coal, hard coal and coal coke; light, medium, and heavy oil) by smoothly transitioning between fuel splits by aggregate sector from the IEA data to SPEW fuel type splits in earlier time periods. Finally fuel use was disaggregated into sectors in a similar manner, smoothly transitioning between CEDS sectoral splits in either 1970 or 1960 to SPEW sectoral splits by
595 1850. A number of exogenous assumptions about fuel and sector splits over time were also needed in this process. More detail on this method can be found in supplement SI-Text Sect. 8.1.1.

While most biomass fuels are consumed in the residential sector, whose estimation was described above (Sect. 2.2.1), biomass consumed in other sectors are extended using SPEW
600 energy data and population. 1970 CEDS estimates of biomass used in industrial sectors are merged to SPEW values by 1920. Biomass estimates from 1750 – 1850 are estimated by assuming constant per-capita values.

Activity drivers for non-combustion sectors in modern years are primarily population estimates. Most historical drivers for non-combustion sectors are also population, while some, shown in
605 Table 4, are extended with other data. These are mostly sectors related to chemicals and solvents that are extended with CO_2 trends from liquid fuel use. Waste combustion is estimated by historical trends for pulp and paper consumption. The driver for sectors 1B2 and 1B2d, refinery and natural gas production, is extended using CDIAC CO_2 emissions for liquid and gas fuels.

610 **Table 4 Historical Driver Extensions for Non-Combustion Sectors**

Non-Combustion Sector	Modern Activity Driver	Historical Extension Trend

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1B2_Fugitive-petr-and-gas	Refinery and natural gas production	CDIAC – liquid and gas fuels CO_2
1B2d_Fugitive-other-energy	Refinery and natural gas production	CDIAC – liquid and gas fuels CO_2
2B_Chemical-industry	population	CDIAC – liquid fuels CO_2
2D_Degreasing-Cleaning	population	CDIAC – liquid fuels CO_2
2D_Paint-application	population	CDIAC – liquid fuels CO_2
2D3_Chemical-products-manufacture-processing	population	CDIAC – liquid fuels CO_2
2D3_Other-product-use	population	CDIAC – liquid fuels CO_2
2L_Other-process-emissions	population	CDIAC – liquid fuels CO_2
5C_Waste-combustion	Pulp and paper consumption	
7A_Fossil-fuel-fires	population	CDIAC – cumulative solid fuels CO_2
All Other Process Sectors	population	

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2.5.2 Pre-1970 emission factors

In 1850, the only fuels are coal and biomass used in residential, industrial, rail, and international shipping sectors, and many non-combustion emissions are assumed to be zero. Emission factors are extended back in time by converging to a value in a specified year (often 0 in 1850 or 1900), 620 remaining constant, or following a trend. For some non-combustion emissions, we use an emission trend instead of an emission factor trend. Ideally, sector-specific activity drivers would extend to zero, rather than emissions factors; however, we often use population as the activity driver, because of the lack of complete, historical trends. Extending the emissions factor (e.g., the per capita value) to zero approximates the decrease to zero in the actual activity.

625 BC and OC emission factors for combustion sectors were extended back to 1850 by sector and fuel using the SPEW database and held constant before 1850. Combustion emission factors for NO_x, NMVOC, and CO in 1900 are drawn from a literature review, primarily Winijkul et al (2016). These emission factors were held constant before 1900 and linearly interpolated between 1900 and 1970. Additional data sources and details are available in the SI-Text Sect. 8.2.

630 Many non-combustion emissions were trended back with existing data from the literature. These include trends from SPEW (Bond et al., 2007), CDIAC (Boden et al., 2016), sector specific sources such as SO_2 smelting and pig iron production, and others, detailed in Table 5. Emissions factors for remaining sectors were linearly interpolated to zero in specified years based on a literature review ((Bond et al., 2007; Davidson, 2009; Holland et al., 2005; Smith et al., 2011)). Further 635 methods and data sources are found in SI-Text Sect. 8.3.

NH_3 and NO_x emissions from mineral and manure (3B_Manure-management and 3D_Soil-emissions) are grouped together. While CEDS total estimates should be reliable, there might be inconsistencies going back in time. We assume that the dominant trend from 1960 to 1970 is mineral fertilizer, then scaled back in time globally using Davidson et al. (2009).

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Table 5 Historical Extension Method and Data Sources for Emission Factors

Sector	Emission Species	Extension Method	Data Source
All Combustion Sectors	NMVOC, CO, NO_X	Interpolate to value in 1900	Detailed in SI-Text (Sect. 8.2.1)
All Combustion Sectors	BC, OC	EF trend	SPEW
2Ax_Other-minerals, 2D_Degreasing-Cleaning, 2D_Paint-application, 2D3_Chemical-products-manufacture-processing, 2D3_Other-product-use, 2H_Pulp-and-paper-food-beverage-wood, 2L_Other-process-emissions, 5A_Solid-waste-disposal, 5C_Waste-combustion, 5E_Other-waste-handling, 7A_Fossil-fuel-fires	All	Interpolate to zero in specified year [EFs are emissions per capita values]	Detailed in SI-Text (Sect. 8.3.1)
5D_Wastewater-handling,	NH_3	Interpolate to value in specified year	
3B_Manure-management	NH3, NO_X	EF trend Emissions trend	Manure Nitrogen per capita (Holland et al., 2005) See SI-Text (Sect. 8.3.1)
3D_Soil-emissions	NH3, NO_X	EF trend Emissions trend	1961-1970: Emissions trend using total nitrogen (N) fertilizer by country 1860-1960: per-capita emissions scaled by global N fertilizer (Davidson, 2009) See Supplemental Information (Sect. 8.3.1)
1A1a_Electricity-public, 1A1a_Heat-production, 1A2g_Ind-Comb-other, 1A3c_Rail, 1A4a_Commercial-institutional, 1A4b_Residential	SO2	EF trend	(Gschwandtner et al., 1986)
1A1bc_Other-transformation	BC, OC	Emissions Trend	Pig iron production (SPEW, USGS, other)
1A1bc_Other-transformation	others	Emissions Trend	Total fossil fuel CO2 (CDIAC)
2A1_Cement-production, 2A2_Lime-production	-	Emissions Trend	CDIAC Cement CO2
2C_Metal-production	SO2	Emissions Trend	Smith et al. (2011) Emissions
2C_Metal-production	CO	Emissions Trend	Pig iron production
2C_Metal-production	others	Emissions Trend	CDIAC solid fuel CO2

650 ## 2.6 Gridded emissions

Final emissions are gridded to facilitate use in Earth system, climate, and atmospheric chemistry models. Gridded outputs are generated as CF-compliant NetCDF files (http://cfconventions.org/). Aggregate emissions by country and CEDS sector are aggregated to 16 intermediate sectors (Table 6) and downscaled to a 0.5 x 0.5 degree grid. Country-aggregate emissions by
655 intermediate gridding sector are spatially distributed using normalized spatial proxy distributions

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for each country, plus global spatial proxies for shipping and aircraft, then combined into global maps. For grid cells that contain more than one country, the proxy spatial distributions are adjusted to be proportional to area fractions of each country occupying that cell. Gridded
660 emissions are aggregated to 9 sectors for final distribution: agriculture, energy, industrial, transportation, residential/commercial/other, solvents, waste, international shipping, and aircraft (shown in Table 6, more detail in SI-Text Sect 9.1).

Proxy data used for gridding are primarily gridded emissions from EDGAR v4.2(EC-JRC/PBL, 2012) and HYDE population (Goldewijk et al., 2011). Flaring emissions use a blend of grids
665 from EDGAR and ECLIPSE (Klimont et al., 2017a). Road transportation uses the EDGAR 4.3 road transportation grid, which is significantly improved over previous versions (EC-JRC/PBL, 2016), but was only available for 2010, so this is used for all years. When the primary proxy for a specific country/region, sector, and year combination is not available, CEDS uses gridded population from Gridded Population of the World (GPW) (Doxsey-Whitfield et al., 2015) and
670 HYDE as backup proxy. Whenever available, proxy data are from annual gridded data, however proxy grids for sectors other than RCO (residential, commercial, other) and waste are held constant before 1970 and after 2008. Specific proxy data sources are detailed in Table 6. As noted above, these proxy data were used to distribute emissions spatially within each country such that country totals match the CEDS inventory estimates. More detail on gridding can be
675 found in the SI-Text Sect. 9.

Emissions are aggregated to 9 final gridding sectors (Table 6) and distributed over 12 months using spatially-explicit, sector-specific, monthly fractions, largely from the ECLIPSE project, except for international shipping (from EDGAR) and aircraft (from Lee et al. (2009), as used in Larmarque et al. 2010). Emissions are then converted to flux (kg m^{-2}s^{-1}). This process is further
680 described in the SI-Text Section 9.4.

Table 6 Proxy Data used for Gridding

CEDS final gridding sector	CEDS intermediate gridding sector definition	Proxy Data Source	Years
Residential, commercial, other (RCO)	Residential, Commercial, Other (Residential and Commercial)	HYDE Population (Decadal values, interpolated annually)	1750 - 1899
		EDGAR v4.2 (1970) blended with HYDE Population	1900 - 1969
		EDGAR v4.2 RCORC	1970 – 2008
	Residential, Commercial, Other (Other)	HYDE Population (Decadal values, interpolated annually)	1750 - 1899
		EDGAR v4.2 (1970) blended with HYDE Population	1900 - 1969
		EDGAR v4.2 RCOO	1970 – 2008
Agriculture (AGR)	Agriculture	EDGAR v4.2 AGR	1970 – 2008
Energy sector (ENE)	Electricity and heat production	EDGAR v4.2 ELEC	1970 – 2008
	Fossil Fuel Fires	EDGAR v4.2 FFFI	1970 – 2008
	Fuel Production and Transformation	EDGAR v4.2 ETRN	1970 – 2008

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	Oil and Gas Fugitive/Flaring	ECLIPSE FLR 1990, 2000, 2010 EDGAR v4.2 ETRN (1970 - 2008)	1970 – 2010
Industrial sector (IND)	Industrial Combustion	EDGAR v4.2 INDC	1970 – 2008
	Industrial process and product use	EDGAR v4.2 INPU	1970 – 2008
Transportation section (TRA)	Road Transportation	EDGAR v4.3 ROAD (2010)	1750 – 2014
	Non-road Transportation	EDGAR v4.2 NRTR	1970 – 2008
International shipping (SHP)	International Shipping	ECLIPSE + additional data (1990 – 2015)	1990 - 2010
	International Shipping (Tanker Loading)	ECLIPSE + additional data (1990 – 2015)	1990 - 2010
Solvents production and application (SLV)	Solvents production and application	EDGAR v4.2 SLV	1970 – 2008
Waste (WST)	Waste	HYDE Population, GPW v3 (modified rural population)	1750 – 2014
Aircraft (AIR)	Aircraft	CMIP5 (Lamarque et al., 2010; Lee et al., 2009)	1850 - 2008
* Spatial proxy data within each country is held constant before and after the years shown. See Supplement for further details on the gridding proxy data including definitions for the EDGAR gridding codes in this table.			

2.7 Additional methodological detail

700 The above sections discuss the general approach to the methodology used in producing this data set, but there are a number of exceptions, details on additional processing and analysis, and data sources that are discussed in the Supplemental files.
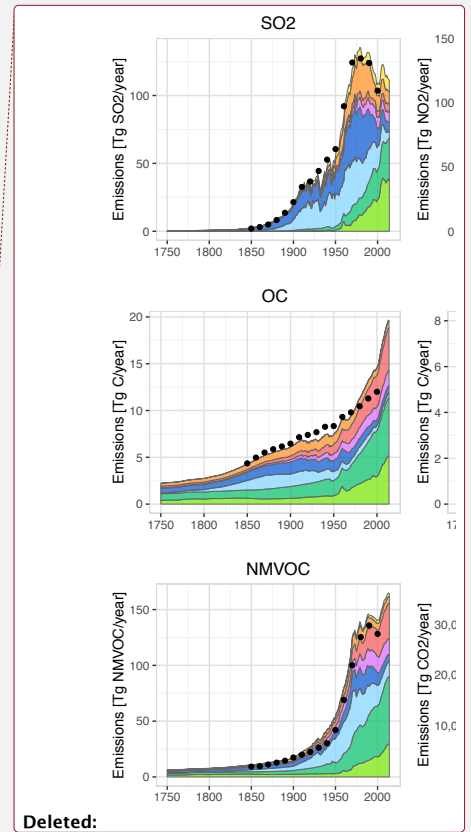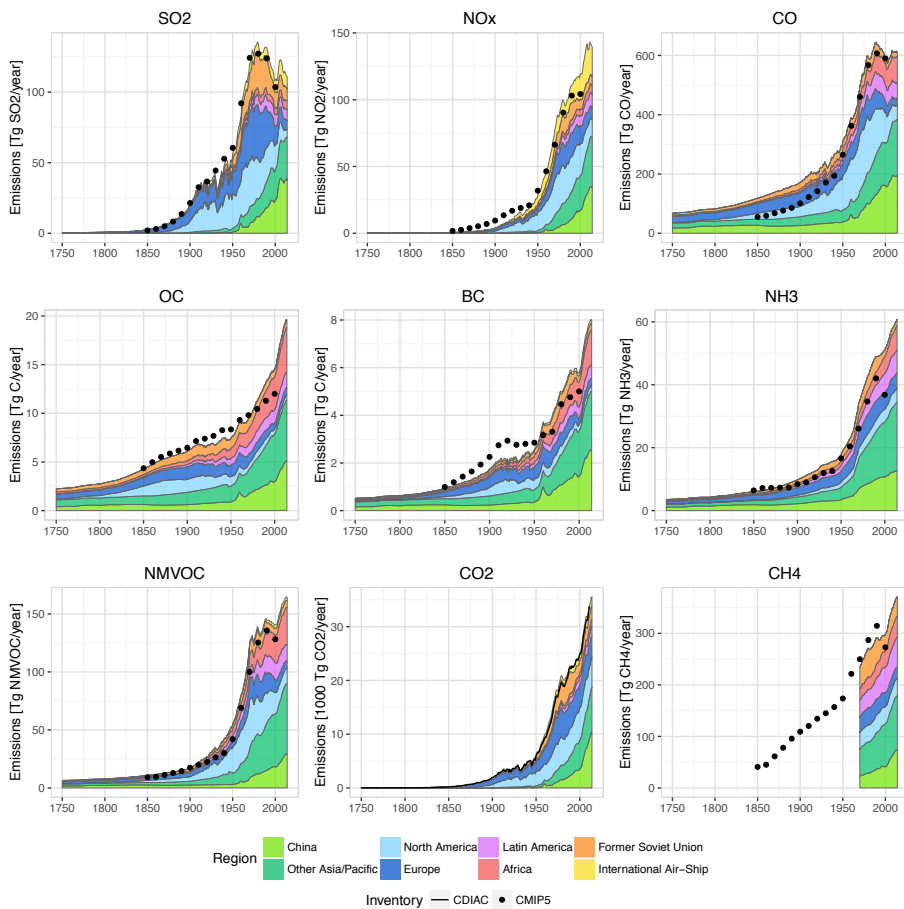
3 Results and discussion

3.1 Emissions trends

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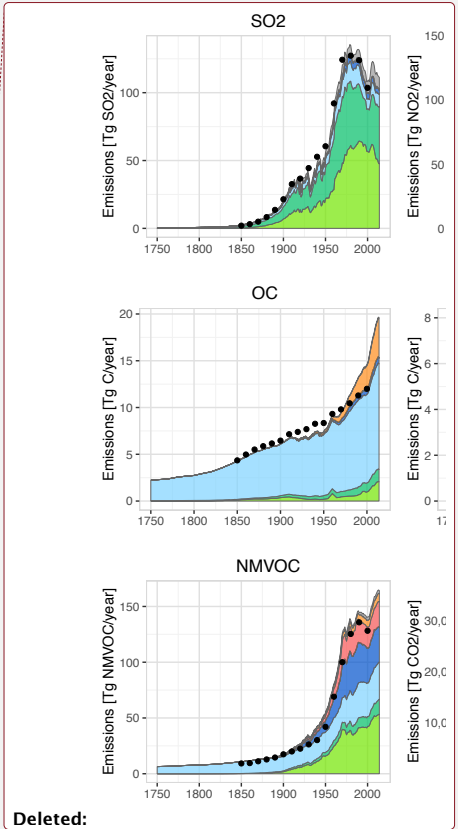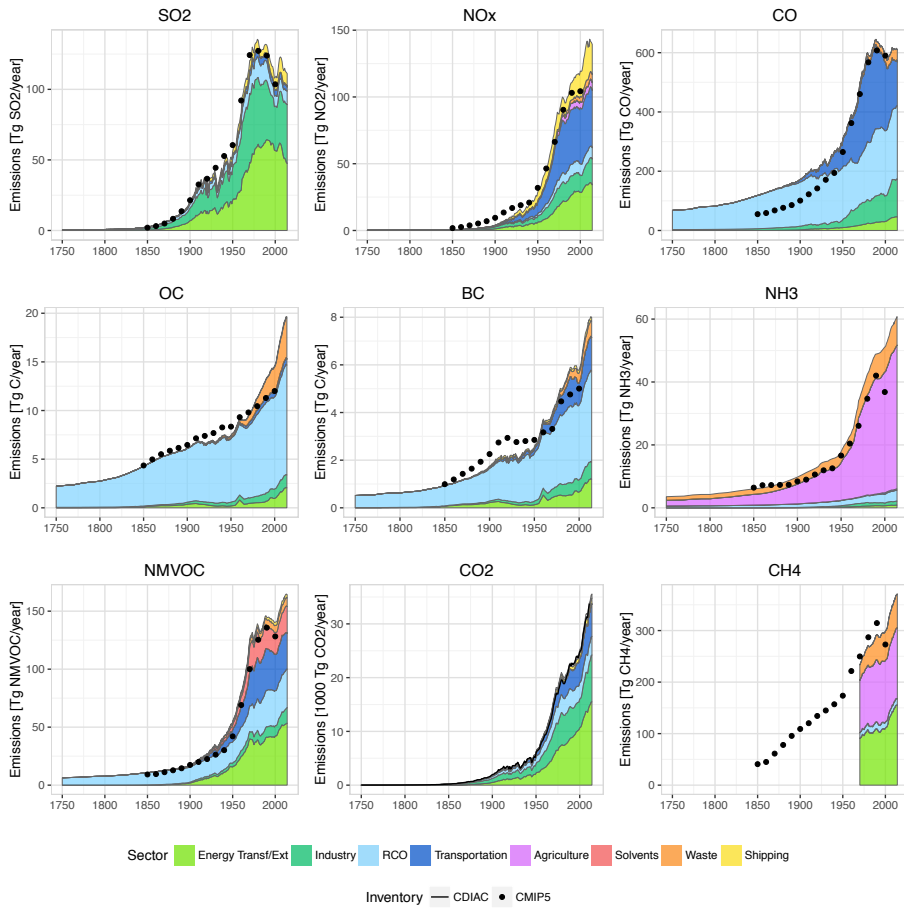
Figure 2: CEDS emissions estimates by aggregate sector compared to Lamarque et al. (2010) (dots) and CDIAC (line) for CO₂. For a like with like comparison, these figures do not include aviation or agricultural waste burning on fields. 'RCO' stands for residential, commercial, and other.

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720   **Figure 3: Emissions estimates by region compared to Lamarque et al. (2010) (dots) and CDIAC (line) for CO₂. For a like with like comparison, these figures do not include aviation or agricultural waste burning on fields.**

Figure 2 and Figure 3 show global emissions over time by aggregate sector and region, respectively, from 1750 – 2014. Definitions of aggregate sectors and regions are given in Supplemental Figure and Tables, Sect. A. The supplement Sect. B contains line graph versions of
725   these figures, emissions by fuel, and regional versions of Figure 2 and Figure 3.

In 1850, the earliest year in which most existing data sets provide estimates, anthropogenic emissions are dominated by residential sector cooking and heating and therefore products of incomplete combustion for BC, OC, CO, and NMVOC. In 1850, anthropogenic emissions (sectors included in this inventory), make up approximately 20 – 30% of total global emissions
730   (which also include grassland and forest burning, estimated by Lamarque et al. (2010)) for BC, OC, NMVOC, and CO but only 3% of global NO$_X$ emissions.

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In the late 1800s through mid 20th century, global emissions transition to a mix of growing industrial, energy transformation and extraction (abbreviated as "Energy Trans/Ext"), and transportation emissions with a relatively steady global base of residential emissions (primarily biomass and later coal for cooking and heating). The 20th century brought a strong increase in emissions of pollutants associated with the industrial revolution and development of the transport sectors (SO_2, NO_x, CO_2, NMVOC). BC and OC exhibit steadily growing emissions dominated by the residential sector over the century, while other sectors begin to contribute larger shares post 1950. The last few decades increasingly show, even at the global level, the impact of strong growth of Asian economies (Fig. 3). The Haber-Bosch invention (ammonia synthesis) about 100 years ago allowed fast growth in agricultural production, stimulating population growth and a consequent explosion of NH_3 emissions (Erisman et al., 2008). Before 1920 global emissions for all species are less than 10% of year 2000 global values.

For several decades after 1950 global emissions grow quickly for all species. SO_2 continues to be dominated by industry and energy transformation and extraction sectors. In the later parts of the century, while Europe and North American SO_2 emissions decline as a result of emission control policies, SO_2 emissions in Asia continue to grow. NH_3 is dominated by the agriculture sectors and NMVOCs by industry and energy transformation and extraction sectors. Transportation emissions have grown steadily and became an important contribution to NO_X, NMVOC, and CO emissions. Growth in CO emissions over the century is due to transportation emission globally until the 1980s and 90s when North America and Europe introduced catalytic converters. Other regions followed more recently resulting in a declining transport contribution, however, CO emissions in Asia and Africa have continued to rise due to population-driven residential biomass burning. Similarly, while NO_X from transportation sectors have decreased in recent years, total global NO_X emissions have increased quickly since 2005 due to industry and energy sectors in all parts of Asia. BC and OC increases since 1950 have been dominated by residential emissions from Africa and Asia but growing fleets of diesel vehicles in the last decades added to the burden of BC emissions.
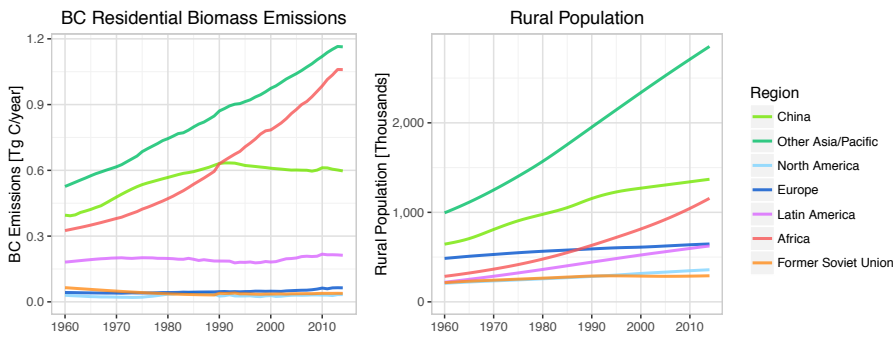
BC emissions from residential biomass are shown in Figure 4 alongside rural population by region. Other Asia, Africa, and China dominate residential biomass BC emissions, which are regions with the largest rural populations. While residential biomass in most regions follow rural population trends, emissions in Latin America stay flat while its rural population has steadily increased since 1960, and emissions in China flatten more dramatically after 1990 than rural population, presumably reflecting the spread of modern energy sources. While rural population in China continually grows, residential biomass use flattens in 1990 as rural residential per capita biomass use decreases in this dataset.

Of the emission species estimated, SO_2 is the most responsive to global events such as war and depressions. SO_2 emissions are primarily from non-residential fuel burning and industrial processes which vary with economic activity, where other species have a base of residential biomass burning or agriculture and waste emissions. In this data set, these emissions remain steady within the backdrop of variable economic conditions, while events such as World Wars or the collapse of the Soviet Union can be seen most clearly in annual SO_2 emissions. We note that the relative constancy of residential and agricultural emissions is, to some extent, a result of a

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lack of detailed time series data for the drivers of these emissions in earlier periods. Variability for these sectors in earlier years, therefore, might be underestimated.

790 **Figure 4: (Left) BC residential biomass emissions by region and (right) rural population by region.**

3.2 Emissions trends in recent years (2000 - 2014)

After 2000, many species' emissions follow similar trends as the late 20th Century, as shown in Figure 5, with further details in the SI-Figures Sect. C, E, and G.

BC and OC steadily grow in Africa and Other Asia from residential biomass emissions, which
795 are driven by continued growth of rural populations. While most BC emission growth in China is due to energy transformation, primarily coke production, the residential, transportation, industry and waste sectors all contribute smaller, but similar growth over 2000 – 2014 (Fig. S19). See Sect. 3.4 for a discussion of uncertainty.

NH_3 continues its steady increase mostly due to agriculture in Asia and Africa. Global CO_2
800 emissions increase due to steadily rising emissions across most sectors in China and Asia and moderately rising emissions in Africa and Latin America, while emissions in North America and Europe flatten or decline after 2007 (largely due to the energy transformation and extraction sectors).

Global CO emissions flatten, despite increasing CO emissions in China and Other Asia, and
805 Africa, which is offset by a continuing decrease of transportation CO emissions in North America and Europe, shown in Fig. 2 and in more detail in the Supplemental Figures. CO emissions in China increase then flatten after 2007, despite continually decreasing transportation CO emissions, which are offset by an increase in industrial emissions (Fig. S19). Similarly, after an increase from 2000 – 2005, global SO_2 emissions flatten despite increasing emissions in
810 China and Other Asia due to steadily decreasing emissions in Europe, North America, and the Former Soviet Union (Figures 2 and S3). SO_2 emissions from energy transformation in China have declined since 2005 with the onset of emissions controls in power plants, however industrial emissions remained largely uncontrolled and became the dominant sector in China (Fig. S19).

815 Global NO_X emissions rise then flatten around 2008. The growth in industrial emissions after 2000 is offset in 2007 by the decrease in international shipping emissions, while global

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830 emissions in other sectors stay flat. NO$_X$ emissions in North America and Europe decline due to transportation and energy transformation (Simon et al., 2015), while emissions in China and Other Asia continue to grow, also in the transportation and energy transformation. Growth of NO$_X$ emissions in Other Asia, almost completely offset reductions in NO$_X$ emissions in North America from 2000 – 2014. In China, industry continually grows since 2003, transportation

835 began to flatten around 2007, and the energy transformation and extraction sectors began declining in 2011 (Fig. S19) following the introduction of more stringent emission standards for power plants (Liu et al., 2016).

Globally, NMVOC emissions increase over the period, due to varying developments across the regions but in large part due to increases in energy emissions. NMVOC emissions increase in

840 China from solvents (Fig. S19), Other Asia from transportation (Fig. S24), and Africa from energy transformation (Fig. S18); decline in Europe and North America due to transportation and solvents (Fig. S20 and S23), and stay flat in other regions.

As discussed in the Sect. 3.5, trends in recent years are more uncertain as they rely on sometimes preliminary activity data and emission factors extended outside inventory scaling years. Some of

845 the notable trends in CEDS emissions estimates in recent years are also from particularly uncertain sources. OC and BC emission estimates have some of the highest degrees of uncertainty in global inventories, and waste sectors in particular are highly uncertain. Additionally, a lot of global growth can be attributed to sectors that, in the CEDS system follow population trends over the most recent few years (e.g. waste, agriculture, and residential

850 biomass); are from inherently uncertain sectors (e.g. waste); or in China where emissions remain uncertain because the accounting of emissions factors, fuel properties, and energy use data have been subject to corrections and subsequent debate (Hong et al., 2017; Korsbakken et al., 2016; Liu et al., 2015b; Olivier et al., 2015).
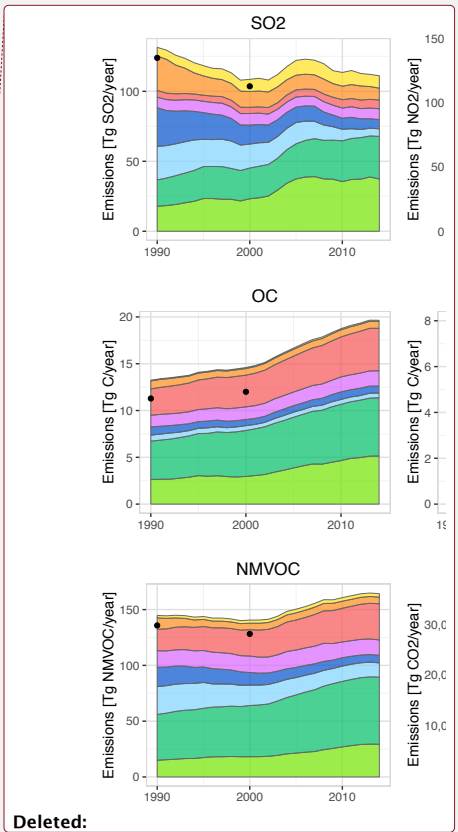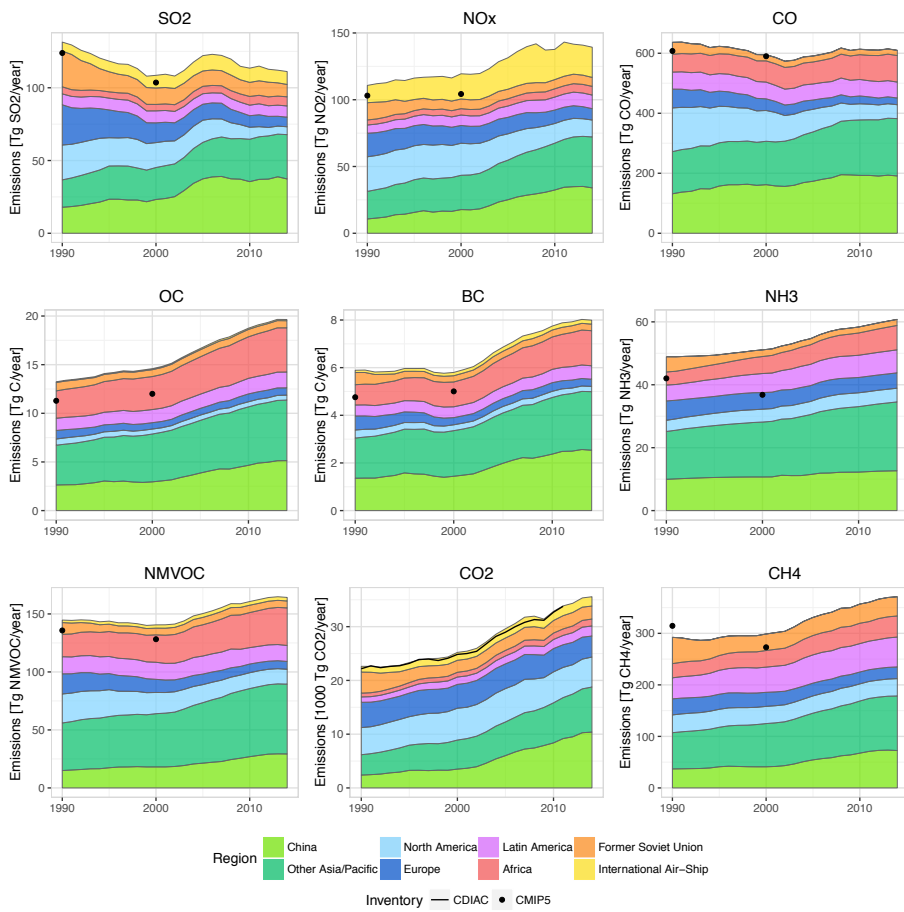
Figure 5: Recent emissions estimates (1990 - 2014) by region compared to Lamarque et al. (2010) (dots) and CDIAC (line) for CO₂. Shows same data as Figure 3 over a shorter time scale. For like with like comparison, these figures do not include aviation or agricultural waste burning on fields.

3.3 Gridded Emissions
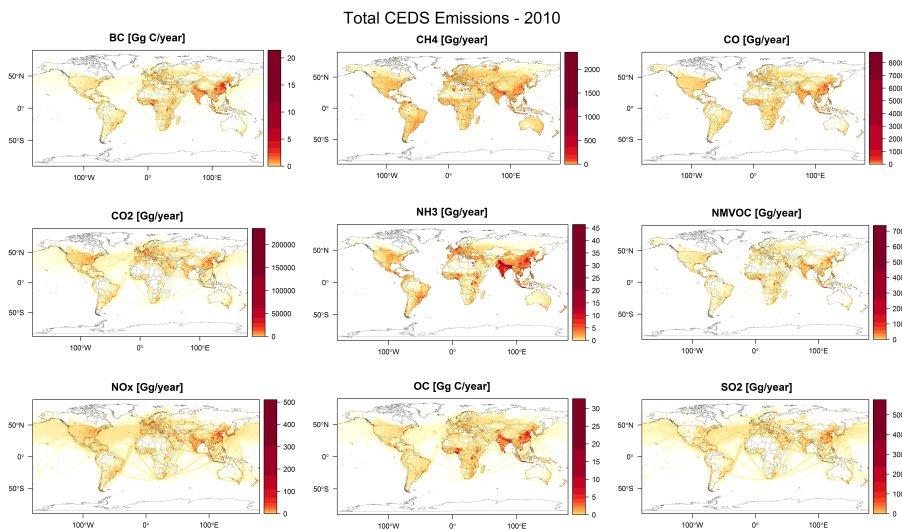
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Total CEDS Emissions - 2010

Figure 6: Total gridded CEDS emissions by emission species for 2010

Figure 6 shows gridded CEDS estimates of total emissions in 2010 for all emission species. CEDS maps are similar to existing maps such as EDGAR (EC-JRC/PBL, 2012) and CMIP5 (Lamarque et al., 2010) as these data sets are used in the gridding process. Emissions for most species are concentrated in high population areas such as parts of China, India, and the eastern US. BC and OC, whose emissions are dominated by heating and cooking fueled by biomass are also more concentrated in Africa. Shipping emissions are concentrated over along ocean shipping lanes for NO_x, SO_2, and CO_2. Discussion of how gridded data varies from CMIP5 (Lamarque et al., 2010) gridded data is included in Sect 3.4.1.

3.4 Comparison with other inventories

Differences between CEDS emissions and other inventory estimates are described below. The reasons depend on emissions species, but are largely due to updated emissions factors, increased detail in fuel and sector data, and a new estimate of waste emissions (however, see Sect. 3.5).

3.4.1 CMIP5 (Lamarque et al., 2010)

The emissions data used for CMIP5 (Lamarque et al., 2010) also used a "mosaic" methodology, combining emission estimates from different sources. The CEDS methodology provides a more consistent estimate over time since driver data are used to produce consistent trends. Emissions in earlier years, particularly before 1900, also differ because CEDS differentiates between biomass and coal combustion, which has a large impact on CO and NO_x emissions. The (Lamarque et al., 2010) estimates for early years were drawn from the EDGAR-HYDE estimates (van Aardenne et al., 2001), which did not distinguish between these fuels. Figures showing comparisons between CMIP5 and CEDS globally by sector and for the top 5 emitting CMIP5 regions are shown in Sect. H of the Figures and Tables Supplement.

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CEDS global SO_2 estimates are very similar to CMIP5 estimates, as similar methods and data were used to develop both estimates (Smith et al., 2011).

CEDS NO_X emissions are smaller than the CMIP5 estimates until the mid-20th century. This is largely because of explicit representation of the lower NO_X emissions from biomass fuels in early periods, which combusts at lower temperatures as compared to coal. In 1970 CEDS NO_X emissions begin to diverge from CMIP5 estimates, generally larger due to waste, transportation, and energy sectors. CEDS emissions remain about 10% larger than CMIP5 in 1980 and 1990. Both global estimates increase and start to flatten around 1990. However, CEDS values flatten until 2000 and then increase again, while CMIP5 values decrease from 1990 to 2000.

CEDS CO estimates before 1960 are increasingly larger than CMIP5 estimates going back in time, reaching a factor of two by 1850 due to the explicit representation of biomass. In 1900, CEDS estimates are 70% larger than CMIP5, 98% of which is due to the RCO sector. CEDS estimates are slightly larger than CMIP5 post 1960 (8% in 1960 and 1970 and less than 5% from 1980 – 2000).

CEDS OC estimates are within 10% but smaller than CMIP5 estimates through 1970, when CEDS estimates quickly increase and become larger (at most 25% larger) than CMIP5 estimates. BC emissions are similar, although CEDS estimates are smaller (sometimes by 25%) than CMIP5 until 1960 when CEDS estimates increase quickly, up to 25% larger than CMIP5 estimates, in part due to larger waste sector emissions (see § 3.5) . Differences in BC in the early 20th century are mostly from residential fuel use in the US. In 1910, 98% of the difference between the two inventories is from residential energy use, with 77% of that difference in the USA. US residential biomass consumption in 1949 is estimated using EIA data and propagated back in time to merge with Fernandes et al. (2007) used by SPEW in 1920. This US biomass estimate may be lower than those used in CMIP5.

NH_3 and NMVOC emissions are similar to CMIP5 estimates until 1950 when CEDS emissions begin to grow at a faster rate than CMIP5 emissions through 1990 when they are about 20-30% larger. Between 1990 and 2000 CMIP5 estimates show a decrease in emissions while CEDS estimates shows flattening emissions then a steep increase. Differences in NH3 emissions are largely due to steadily increasing agricultural emissions and a larger estimate from wastewater/human waste, which makes up 14% of CEDS NH_3 estimates in recent decades but was largely missing in the RCP estimates. CEDS NMVOC emissions are much larger for global waste, while much smaller for global transportation.

Global CEDS CH_4 emissions range from 93% of CMIP5 values in 1970 to 109% of CMIP5 values in 2000. CEDS estimates change more smoothly over time, without a dip in 2000. CEDS energy estimates are consistently larger than CMIP5 emissions, 22 – 58%, while CEDS agriculture emissions are consistently 10-15% smaller than CMIP5 estimates, except in 2000 (6% smaller) when CMIP5 estimates dip and CEDS emissions flatten, due to our inclusion of FAO agriculture data.

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Total emissions difference (CEDS - CMIP5): BC [Gg C/year]
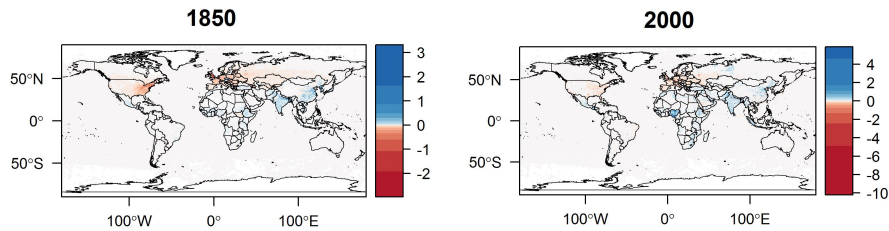
1850   **2000**

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Figure 7 shows differences between total gridded emissions for CEDS and CMIP5 for BC in 1850 and 2000. In 1850, CEDS BC emissions are lower over the eastern US, Europe (especially cities in the UK) and slightly larger over parts of India and China. Larger differences are concentrated in high population areas. However, as with country totals, as emissions in 1850 are quite small, so absolute differences are also small. In 2000, emissions follow a similar pattern. CEDS BC emission are smaller over Europe and the eastern US, but larger over populated areas of India, China, and western Africa (particularly Nigeria), reflecting, in part higher country totals (e.g. Figure S41).

Additional text and similar difference maps for SO_2, NO_X, CO, OC, NH_3, and NMVOC are included in Supplemental Figures and Tables, Section K. Similar to BC, the magnitude of most differences in 1850 are small, as total global emissions are small, and tend to be more concentrated in populated areas. Differences in 2000 are a bit larger, tend to be consistent across countries. For example, total CEDS CO emission in India in 2000 are smaller than CMIP5 values, so most grid cells in India have smaller values. However, differences in gridded SO_2 emissions in 2000 are not as consistent across countries or regions and tend to be highly concentrated into small groups of grid cells. Globally CEDS SO_2 emissions are very similar to CMIP5 emissions, and emissions are dominated by large point sources, so these differences are likely due to updated proxy data for power plants and metal smelters.

BC, OC and NH_3 CEDS emissions in 2000 are larger over India, China, and parts of Africa than CMIP5 estimates, similar to BC emission in Fig. 7. CEDS NO_X emissions in 2000 are also larger over China and India, while they are smaller over the Middle East and Eastern Europe. NMVOC estimates are smaller over China and the Middle East.

As discussed further in the SI (section K), these differences are due to a combination of differences in aggregate country-level emission estimates, spatial proxy data, and methodologies for mapping aggregate emissions to spatial grids. We note that the spatial proxy that is most important will also depend on emission species: for SO_2 power plants will generally be a key sector while for NO_2 mobile sources are often the most important sector.

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3.4.2 GAINS and EDGAR v4.3

CEDS estimates are compared to GAINS and EDGAR v4.3 emissions estimates in Fig. S40, shown in Supplemental Figures and Tables (SI-Figures).

Global CEDS emissions estimates are generally comparable to GAINS global emissions, comparing only sectors common to both inventories. BC, OC, NO_X, and SO_2 CEDS estimates are within +/- 15% of global GAINS values in 2000, 2005 and 2010. In 2000, BC, and SO_2 CEDS emissions are smaller than GAINS values but are larger than GAINS global values by 2010, while CEDS NO_X and CO estimates are consistently larger than GAINS values. CEDS OC and NMVOC emissions are 18 – 44% larger than GAINS emissions. One of the key differences is associated with estimates for waste (trash) burning which are much higher in CEDS (based on Wiedinmyer et al. (2014)) and have a strong influence on totals, particularly OC and NMVOC (see §3.5). Between 2000 and 2010 global CEDS emissions for all species increase more quickly than the GAINS estimates.

CEDS estimates are consistently somewhat larger than EDGAR 4.3 global estimates for all emissions species. CEDS emissions, while slightly larger, follow the same annual trends as EDGAR from 1970 – 2000 or all species but OC. CEDS emissions for OC grow somewhat linearly over the period, while EDGAR estimates stay relatively flat. Sectors driving the differences between CEDS and EDGAR estimates vary by emission species. However, these differences are largely due to waste burning and aggregate sector 1A4, which is dominated by residential emissions, but also includes commercial/institutional, and agriculture/forestry/fishing.

Global CEDS CH_4 emissions estimates are slightly smaller than, but similar to EDGAR 4.2 estimates, ranging from 94 – 98% the EDGAR estimates. The similarity is because much of our methane emissions are either from EDGAR, or FAO (which uses similar methodologies). The largest differences can be found in 1B2 (fugitive petroleum and gas emissions) in Central and South America Africa, and the Former Soviet Union, as these default emissions also incorporate data from ECLIPSE V5a (Stohl et al., 2015), and rice cultivation in China (FAO, 2016).

3.5 Uncertainty

Emission uncertainty estimates in inventories are a critical need, however this is difficult to quantify and most inventories do not include uncertainty estimates. All the components and assumptions used in this analysis are uncertain to varying degrees, which means that uncertainty will vary with time, space, and emission species making quantification of uncertainties challenging.

There are some consistent trends in uncertainty estimates by emission species. Uncertainty is generally lowest for CO_2 and SO_2 emissions, which depend primarily on quality of fossil fuel statistical data and fuel properties, e.g. carbon and sulfur content, with straightforward stoichiometric relationships. Global CO_2 and SO_2 uncertainty has been estimated to be in order 8% for CO_2 (Andres et al., 2012) and 8-14% for SO_2 (Smith et al., 2011), for a roughly 5-95% confidence interval. Global uncertainties for these species tend to be relatively low also because fuel properties are not thought to be highly correlated between major emitting regions.

Uncertainty in specific countries can be much higher, however. China is a major emitter of both CO_2 and SO_2, and uncertainties regarding the level of coal consumption (Guan et al., 2012; Liu et al., 2015b) will directly impact emission estimates as well as actual implementation and

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efficiency of control equipment (Xu et al., 2009, 2009; Zhang et al., 2012). Since China energy consumption uncertainties appear to be largest in sectors with limited emission controls they can have a large impact on SO_2 emissions in particular (Hong et al., 2017).There is also uncertainty regarding the appropriate CO_2 emission factor for coal in China (Liu et al., 2015b; Olivier et al.,
1015 2015) as discussed further in the SI-Text Sect. 5.4.

Emission factors for CO, NO_X, NMVOC, BC and OC, tend to be dependent on details of the emitting process, and, therefore, have higher uncertainties (Blanco et al., 2014). This is particularly true for carbonaceous aerosol emissions, where emission factors can range over several orders of magnitude depending on the conditions under which combustion occurs.
1020 Uncertainties in global BC emissions have been estimated to be a factor of two (Bond et al., 2004). Uncertainty in country-level BC emissions in China were estimated to be –43% to +93% by Lu et al. (2011), -50% to +164% by Qin and Xie (2012) ±176% by Kurokawa et al. (2013a), and -28 to +126% by Zhao et al. (2013b). Uncertainty in activity levels also contributes, with the large uncertainty in biofuel use in many regions contributing to BC and OC emissions
1025 uncertainty.

Emissions uncertainties for CO, NO_X, NMVOC typically lie between those of carbonaceous aerosols and those of CO_2 and SO_2. In part this is because, particularly in industrialized economies, a number of sectors contribute to emissions, and sectoral uncertainties will largely be independent of each other. Substantial uncertainty can still be present for specific sectors, even in
1030 countries with well-developed emission inventory processes (Parrish, 2006). For example, studies combining observations and modeling suggest that recent US national emissions inventory overestimates on road vehicle NO_X emissions by about a factor of two (Anderson et al., 2014; Hassler et al., 2016; Travis et al., 2016), while recent updates of Canadian NMVOC emissions (Environment and Climate Change Canada, 2016) are, for some sectors, a factor of
1035 two larger than previous estimates (Environment Canada, 2013).

There are specific sectors with particularly uncertain emissions. The level of fugitive emissions often depends on procedures and practices, leading to large uncertainty. Emissions that result from biological processes, such as NO_X from fertilized soils or NH_3 from wastewater and agriculture, also generally depend on environmental conditions and would, in principle, require
1040 detailed modeling to improve estimates. Our NH_3 emissions from human waste, for example, follow REAS (Kurokawa et al., 2013a) and uses a single global default emission factor (modified to account for wastewater treatment as described in the SI). Not only is this emission factor uncertain, but there will certainly be regional variations due to differing environmental conditions that we were unable to take into account. For agricultural emissions, the actual
1045 practices of managing livestock manures will affect true emissions; such practices vary significantly across the world but are not always well understood or reflected in the emission factors used in global inventories (Paulot et al., 2014). We note that in the CEDS historical extrapolation before either 1960 or 1970, depending on the sector, global trends were used for agricultural emissions, which means that country-specific trends were not taken into account,
1050 leading to additional uncertainties at the country level.

Residential waste burning emissions depend on the amount of waste combusted, composition of the waste, and combustion conditions. This sector globally contributes a substantial fraction of OC emissions in particular, but substantial amounts of BC and other species. The CEDS estimate for this sector, except where scaled to country emission estimates (available only in a few OECD
1055 countries) is based on 2010 estimates from Wiedinmyer et al. (2014). Wiedinmyer et al. followed

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IPCC guidelines and assumed that 60% of all waste that is not reported as collected is burnt. This could be an overestimate in countries where there is informal waste collection and recycling. Klimont et al. (2017a) recently estimated BC and OC emissions from this sector, estimating that from 115 to 160 Tg of waste was openly burned, while Wiedinmyer et al. (2014) derive a value
1065 of 970 Tg. It is possible that the CEDS values, therefore, are overestimates of emissions from this source. Note, however, that the Wiedinmyer et al. (2014) estimate only includes residential waste burning. In the USA, for example, a large portion of CO_2 from waste burning is from industrial waste, particularly from tires (US EPA, 2015), which implies there will also be additional air pollutant emissions from industrial waste combustion. Outside of the specific
1070 OECD countries where country-specific inventories include this sector, industrial waste estimates were not explicitly included in the CEDS estimates. Overall there is substantial uncertainty for emissions from this sector.

All other factors being equal, uncertainty will tend to increase backwards in time, as driver data becomes more uncertain and older technologies are used, for which emission factors are not well
1075 quantified. We generally expect that uncertainty in this data set will be smaller for those years and countries where robust inventory development mechanisms are in place. However, as noted above for NO_X in the USA, this does not eliminate uncertainty. Official country inventories can sometimes be developed with outdated methodologies or can be incomplete. Many countries have regular evaluation activities, which indicate deficiencies and potential areas for
1080 improvement. However, assessments of completeness and plausibly are always useful, and inventories developed for scientific use, including CEDS, can help contribute in this area.

Our data system also allows us to examine the emission factors implied by scaling to country inventories. This can reveal potential inconsistencies or regional differences. One example is shown in Figure 8, which shows the implied emission factor for CO emissions from gasoline
1085 road vehicles. Even where there is a mix of fuels in the road sector, the much higher CO emission factor for gasoline tends to lead to gasoline dominating emissions, making this comparison a fairly unambiguous reflection of underlying inventory assumptions. There is over a factor of two difference in implied emission factors before 1990, with some inventories indicating steadily increasing emission factors going back in time while others flatten out. It is
1090 unclear if these differences are due to local variations in vehicle types, operation, or environmental conditions, or if differences reflect inventory assumptions, which implies some inventories might be biased high or low.
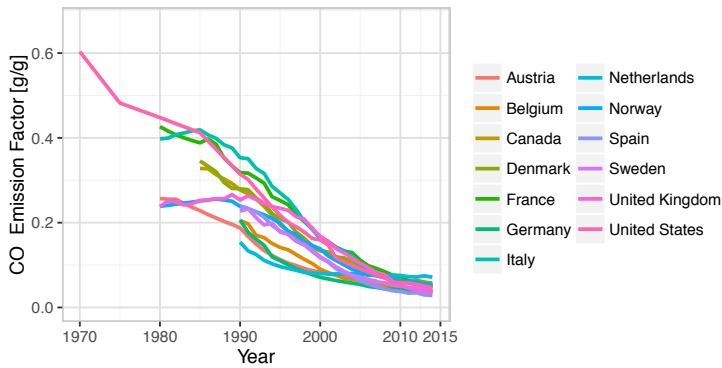
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Figure 8: Implied CO emissions factor for gasoline road vehicles obtained by the CEDS system after scaling to match country inventories. Data points only shown where an inventory value was available in units of g CO/g fuel.

1100   There are specific issues with uncertainty over the most recent few years in most emission data sets. We have, in this data set, provided emissions up to 2014. Emissions estimated for the most recent several years are likely to have larger uncertainty due to the use of incomplete or preliminary data. Uncertainty in recent years comes from three main sources: activity data, emissions inventories that are used in our estimate, and the treatment of emission factors.

1105   Uncertainty from activity data comes from both uncertainty in country totals and their sector split. While activity data are often updated annually, recent estimates sometimes change for a few years after their initial release. For example, the BP estimate of Russian coal use in 2012 may be different in the 2013, 2014, and 2015 data releases. The BP estimates we use to extrapolate fuel use for the most recent 2 years (Sect. 2.2.1) also lacks sectoral detail, which adds

1110   to uncertainty. Values in the inventory estimates we use in this data set for the most recent year are often preliminary and are later revised, which is an additional source of uncertainty.

Finally, we use emission factor trends from GAINS to project emission factors for combustion sectors for recent years beyond where inventory data are available. The last inventory year varies: 2010 for EDGAR, which is our default inventory for most species, 2008 for REAS, 2012

1115   for China, 2013 for most of Europe, and 2014 for the USA. Using emissions factor trends that are not from detailed country-specific inventories is an additional source of uncertainty.

In future versions of CEDS, quantitative uncertainty analysis will be included for all time periods, but is not complete as of the CMIP6 data version.

4   Comparisons with observations

1120   It is challenging to evaluate emissions against observations since, other than facility-specific emissions monitors, emissions concentrations are observed rather than emissions fluxes into the atmosphere. Satellite data (Jacob et al., 2016; Streets et al., 2013), road-side measurements (Pant and Harrison, 2013), and inversion of surface observations (Bruhwiler et al., 2014; Houweling et al., 2017) can all be used to estimate emissions using observational data. These techniques can be

1125   used to gain insights into the accuracy of emission inventories, although each has associated

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1130 uncertainties. Emission ratios are a particularly valuable technique, and we compare in this section CEDS data with observations for two cases.

Hassler et al. (2016), compare observed ambient NO_x/CO enhancement ratios (measurements taken during morning rush hour) with NO_x/CO road emissions trends for London, Paris, and several US cities. Hassler et al. compare to the MACCity inventory (Granier et al., 2011), which
1135 is based on CMIP5 (Lamarque et al., 2010) inventory estimates and RCP projections. They find that log linear trends in observed ratios in US cities, London, and Paris are steeper than MACCity ratios by a factor of 2.8 – 5.5. CEDS country-level NO_x/CO emissions ratios match observed trends much closer than MACCity, where observed trends are only 2-18% steeper than CEDS trends, shown in Table 7. Further, CEDS gridded road emissions, match even better with
1140 the observed trends for London and Paris..

Table 7 Trends in Observed and Inventory NO_x/CO emission ratios

City/Country	Years	Observed*	MAACity*	CEDS (gridded - road)	CEDS aggregate (road)	CEDS (total)
USA (various cities)	1989-2013	4.1	1.45		3.86	2.37
UK (London)	1989-2015	7.2	1.88	6.92	6.90	5.90
France (Paris)	1995-2014	8.8	1.59	8.09	7.47	3.39
Values shown in log linear trends in units of %yr^{-1} *(Hassler et al., 2016)						

Kanaya et al. (2016) present observations of BC/CO ratios over six years (2009 – 2015) at Fukue Island, Japan, which, depending on wind conditions, gives region specific emission ratios under
1145 dry conditions for Japan, Korea, and four regions in China, shown in Table 8 compared to CEDS and REAS BC/CO emissions ratios, both of which do not include open biomass burning. Both CEDS and REAS emissions ratios are similar to observed ratios for Japan, 1.64 and 1.1 times larger than observed ratios respectively, but near the observational uncertainty. The 2008 – 2015 average CEDS emission ratio is 2.1 – 2.7 times larger than observed ratios over China regions.
1150 CEDS emissions ratios are substantially larger than both observed and REAS ratios for Korea. Kanaya et al. attribute the difference between REAS and observations in Korea to the overestimation of industry and transportation BC/CO ratios in inventories. CEDS Korea, sector-specific BC/CO emissions ratios are high compared to observations: 370 and 41 ngm^{-3}ppb^{-1} for industry and transportation sectors respectively compared to 42 and 27 ngm^{-3}ppb^{-1} in REAS.
1155 CEDS CO estimates, which are scaled to Korean national inventory from 1999 – 2012, are 5 – 47% lower than REAS2.1 estimates over 2000 – 2008. CEDS CO emission estimates are dominated by energy transformation (20%) and transportation 68%. CEDS BC estimates use SPEW assumptions. CEDS BC emissions estimates for Korea are 5-8 times larger than REAS estimates. While CEDS estimates are larger over all sectors, the other transformation (e.g. coal
1160 coke production) and road sectors are the primarily sources. Emissions from the CEDS other transformation sector, which are zero in REAS estimates, makes up 35% of CEDS Korea estimates. CEDS Road BC emissions over 2000 - 2008 are 2-3 times larger than REAS estimates and 34% of the CEDS total.

These comparisons are approximate, given that the CEDS data represents entire countries and the
1165 air trajectories sampled at Fukue Island will preferentially sample only portions of each country. In future versions of CEDS we plan to produce emissions for large countries such as China at the

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province level which will aid in such comparisons. In general, differences in these ratios could be attributed to the overestimation of BC, underestimation of CO emissions, or both. Overall, CEDS emissions appear consistent for Japan, but perhaps slightly too high for China. CEDS BC estimates for Korea are quite high compared to other inventories and the observations, and suggest that the SPEW emission factors for Korea may not have incorporated the impact of transportation emission controls and new technologies for coal coke production.

Table 8 Observed and Inventory BC/CO emission ratios

Country	Observed* 2009 - 2015 [ΔBC/ΔCO]	CEDS 2009 - 2014 [BC/CO]	CEDS 2008 [BC/CO]	REAS2.1 2008 [BC/CO]
Japan	5.9 ± 3.4	9.7	9.5	6.5
Korea	6.7 ± 3.7	89.8	82.3	23
China (North East)	6.0 ± 2.8			
China (North Central East)	5.3 ± 2.1			8.3
China (South Central East)	6.4 ± 2.2	14.3	12.8	9.9
China (South)	6.9 ± 1.2			
Values shown in $ngm^{-3}ppb^{-1}$ * (Kanaya et al., 2016)				

These examples illustrate that further comparisons would be of substantial value in better resolving emissions. The use of multiple observations and methodologies would add confidence to conclusions regarding the accuracy of emission inventory data.

5   Limitations and future work

While this data set includes many improvements upon existing comprehensive, long-term inventories, there are some specific limitations of the current methodology, and plans for improvement, that we discuss here.

Disaggregation of key non-combustion sectors, particularly 1A1bc_Other-transformation and 2C_Metal-production, should allow a more accurate estimation of emissions trends. This will require collection of additional activity data and default emission factors. At the current level of aggregation, emission trends for these sectors will be less accurate, particularly for years where country-level emission data sets are not available.

Emissions trends could be further improved for the mid-20th century. Emission factors here are often the result of scaling at later inventory years (e.g. Fig. 4), and further work to better constrain emission factors over this period is needed. The sectoral spilt for fuel use is also approximated over this period; incorporation of regional activity data would improve this as well. Non-combustion emissions are particularly uncertain in the era before modern inventory data sets, which is generally before 1970/1980, since these emissions can depend on process details.

We plan to incorporate more detailed data from the US National Emissions Inventory, although as with the current estimate, discontinuities due to methodological changes will need to be

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addressed. Use of this data to estimate emissions at the US state level is underway, which will also be used to improve the spatial gridding of emissions over time.

Currently, a number of gridding proxies are static over time. Residential (and related) emissions are distributed using population distribution, which does change over time. Because residential emissions are dominant in earlier years, much of the major shifts in spatial   distribution with a country are being captured. Other sectors have mix of spatial proxies, few of which are newer than 2010, and many were kept static over time. Consistent data sets over time for spatial proxy information would be a useful addition.

A major next step in this project will be estimation of uncertainty. Our first step will be quantification of the additional uncertainty that stems from producing estimates out to the most recent full year, followed by comprehensive uncertainty estimates that will be used to produce ensembles of emissions to more fully reflect the uncertainty in these data.

In addition to updates, refinements, and uncertainty analysis, the CEDS system will be released as open-source software, along with associated input data. Where previous work has only released final emissions estimates, this entire data system will be released to facilitate evaluation of trends in and the relationships between emissions, emission factors, and their drivers across time, countries, sectors, and fuels; to foster transparency in assumption and methods; and allow community input and participation. While the current data system requires purchase of the IEA energy statistics, we will explore options to facilitate use with publically available data as well.

6   Summary

This paper described the methodology and results for a new annual data set of historical anthropogenic GHGs, reactive gases, aerosols, and aerosol and ozone precursor compounds from 1750 to 2014 for use in CMIP6. This data set relies heavily on IEA energy statistics, EDGAR, and other inventory data sets to produce consistent trends over time. Key steps in estimating emission include collecting existing activity, emissions factors, and emissions data; developing default emissions estimates; calibrating default estimates to existing inventories; extending present day emission to historical time periods; and gridding emissions.

Emissions before 1850 are dominated by residential biomass burning and agricultural emissions. As the industrial revolution expanded, energy, industry, and transportation related emissions then begin to grow and then quickly increase in the mid 20th century. Emissions of some species begin to slow or see global reductions in the late 20th century with the introduction of emission control policies, but emissions of many of those species increase again in recent years due to increased economic activity in rapidly industrializing regions. While comparable to existing data sets such as CMIP5 (Lamarque et al., 2010), EDGAR (EC-JRC/PBL, 2016), and GAINS (Amann et al., 2011; Klimont et al., 2017a), CEDS estimates are generally slightly higher than those inventories in recent years.

Future work on this data system will involve refining and updating these emissions estimates, adding detail, and the release of the CEDS as an open source data system. In order to be able to release the current data set in time for use in CMIP6, the focus was on the development and use of a consistent methodology, relying in large part on IEA energy statistics and existing inventory data over recent years. As described above and in the SI, a number of additions were made where inconsistencies or incompleteness in these core data sets were known and improved data

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were readily available. There are many further corrections that would likely be useful to
implement. For example, the inventories used here for calibration may already be known to
contain deficiencies, for example through regular validation activities. There are likely also
country level energy and other driver data that can be used to improve the data used here.
Finally, further detailed comparisons with observations may help to indicate additional areas
where changes to emission factor or other assumptions are warranted.

With release of this data set, and soon the entire data system, it is our intention that further
improvements will be made through feedback from the global emissions inventory community.
The CEDS data system, including R code and all input data other than the IEA energy statistics,
is being prepared for public release in fall 2017 through the gitHub collaboration website. This
will facilitate community comment, and direct contributions to improving these emissions data.
The next data release is planned for Fall/Winter 2017, which will extend the time series to 2016
and correct, to the extent possible, any known issues with the dataset. We aim to continue annual
updates in subsequent years. We welcome comments, including notes on any
potential inconstancies or relevant new data sources, so that that these data can be improved in
future releases.

Data Availability

Gridded versions of this data are available through the Earth System Grid Federation (ESGF)
[https://esgf-node.llnl.gov/search/input4mips/] under the activity_id = "input4MIPs" and
institution = "PNNL-JGCRI". More information on the CEDS project, system release, and
updates, can be found at http://www.globalchange.umd.edu/ceds/. Note that known issues with
the data are listed at https://github.com/JGCRI/CEDS and users can also submit issues via the
GitHub site.

Author Contributions:

R.M. Hoesly and S.J. Smith prepared the manuscript with contributions from L. Feng, Z.
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The CEDS system was developed by R.M. Hoesly, S.J. Smith, L. Feng, T. Pitkanen, J.J. Seibert,
L. Vu, and R. Bolt. Analysis was performed by R.M. Hoesly, S.J. Smith, L. Feng, L. Vu, M.C.P.
Moura, N. Kholod, and P. O'Rourke. Data were contributed by Z. Klimont, G. Janssens-
Maenhout, R.J. Andres, T.C. Bond, L. Dawidowski, J. Kurokawa, M. Li, L. Liu, Z. Lu, and Q.
Zhang.

Competing Interests

The authors declare that they have no conflict of interest.

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Research (BER) programs and performed at Oak Ridge National Laboratory (ORNL) under U.S. Department of Energy contract DE-AC05-00OR22725.

A1 Supplementary information files

Supplementary files related to this article include:

Supplemental Data and Assumptions Text (pdf)

Supplemental Figures and Tables (pdf)

Data Files (zipped set of csv files)

- Emissions by country and sector (all species)
- Global emissions by sector (all species)
- Total emissions by country (all species)
- Country mapping and ISO codes

The supplementary information for this article describes a number of additional data sources used in this work, including the following:

(Bartoňová, 2015; Blumberg et al., 2003; Denier van der Gon et al., 2015; EIA, 2013; Endresen et al., 2007; Environment Canada, 2016; Eyring et al., 2005; Fletcher, 1997; Foell et al., 1995; Fouquet and Pearson, 1998; Gschwandtner et al., 1986; Huo et al., 2012; IEA, 2016a; Kaur et al., 2012; Kholod and Evans, 2015; Liu et al., 2015a; Ludek and Holub, 2009; McLinden et al., 2016; Mester, 2000; Mitchell, 2003, 2007, 1983; Mylona, 1996; OECD, 2016; Pretorius et al., 2015; Rowe and Morrison, 1999; Ryaboshapko et al., 1996; Sanger, 1997; Simachaya, 2015; Smith et al., 2014; Tushingham, 1996; UK DEFRA, 2015; US EPA, 2012a; Wu et al., 2012; Zhou et al., 2011)

A2 Data Release and Known Issues

A2.1 Known Issues

This section lists known issues with the data released as of this writing (August 2017). Readers should refer to the project web site for general updates (globalchange.umd.edu/CEDS) and the project's github site for an updated list of issues (https://github.com/JGCRI/CEDS)..

- Combustion emissions become zero in earlier years for several countries that have inconsistent temporal coverage in the IEA energy data. These include: Sint Maarten, Suriname, Cambodia, Mongolia, Palau, Botswana, Namibia, and Niger. Some of these instances, where alternative data sources are available, will be corrected in the next release.

- Some of the countries in the IEA "other" aggregations (e.g. "Other Asia", "Other Africa", and "Other Non-OECD Americas") have spurious sector splits due to the simple methods used to assign fuel use to these countries (e.g. there is fuel use in the Afghanistan international shipping sector).

- There are a few spurious small-magnitude process emissions (particularly in 2C_Metal-production) for smaller countries before 1900 that are artifacts of the extension process. These have negligible impacts on emission totals.

- There are some spurious emission results for early years at the sectoral level in the current database due to the sectoral resolution of the data used to extend emissions back in time. For example, aircraft emissions are present back to 1851, even though actual aircraft emissions did not begin until the early 20th century. The magnitude of these emissions are small and, while these emissions should be zero in early years, these small magnitudes will not materially impact climate model results. (NO_x in the CEDS aviation sector in 1920 is 0.2% of estimated NO_x from lighting (Schumann and Huntrieser 2007), for example, and very much smaller in earlier years.) The historical energy code is being revised to be more flexible to improve our ability to incorporate additional energy data sets including, for example, historical estimates of aircraft fuel consumption.

- Due to an error, SO_2 emissions in the US are overestimated from about 1961 to 1969. The overestimate averages 22% over this period. This has been corrected for inclusion in the next data release. The previous and corrected time series is shown in the supplement.

- SO_2 emissions in the gridded data are overestimated in the western United States relative to the eastern United States. This spatial allocation is present in the EDGAR emission grids used for spatial mapping within each country.

A2.2   Gridded Data Release History

There have been several releases of the CEDS gridded data. The underlying emissions by country, sector and fuel have been identical in all of these releases, as are total emissions by country and gridding sector (with the exception of small changes in 1850 emissions noted below).

v2016-05-20: Pre-industrial 1750-1850 data release

v2016-06-18: 1851 – 2014 data

v2016-06-18-sectorDim: Re-release of both preindustrial and 1851 – 2014 in a new netCDF format with sectors as an additional dimension in the data variable. This reformatting was necessary due to a limitation that was discovered within the ESGF system summer 2016. The reformatted data were released early Fall 2016

v2017-05-18: Re-release of entire dataset in order to correct two gridding errors discovered by users. 1) Inconsistent emission allocation to spatial grids within countries that resulted in incorrect spatial allocations and some large discontinuities in the gridded data. These issues were particularly apparent in spatially large countries such as the USA and China. 2) Minor inconsistencies in seasonal allocation, resulting largely in emissions that were too high in February. Total annual emissions within each country were not impacted by either of these issues.

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Emissions are also fully consistent across 1850 in this release. There were small discontinuities in 1850 between the CEDS CMIP6 preindustrial release (v2016-06-18) and the later full CEDS release (v2016-07-26) due to updates in the data system. These differences are 0.5% for all species (except NMVOC which reaches 1.5%). In absolute terms these differences are very small (relative to, for example, open biomass burning emissions) and will not have a significant impact on simulation results.

A link to further examination of these issues, including comparison maps and time series comparisons, can be found at the project web site (globalchange.umd.edu/CEDS).

A2.3   Methane Historical Extension

As several modeling groups participating in CMIP6 requested CH_4 emissions from 1850. We were not able to extend the consistent CH4 time series before 1970 due to the additional data that would need to be collected and processed. We have, however, produced a "rough cut" supplementary extension of CH_4 emissions from 1850 – 1970 by scaling with CMIP5 historical CH_4 estimates (Lamarque et al. 2010). These estimates were generated by scaling the CEDS 1970 estimates with the CMIP5 trends (ie: shifting CMIP5 trends to match CEDS values in 1970) by aggregate sector and the 26 sub-region level of the CMIP5 data. While these emission estimates are not fully consistent with the other CEDS emissions, they provide a longer time series, albeit with some additional uncertainty, for groups that would like to have these trends. These data are available as supplementary gridded information for CEDS version 2017-05-18 data through ESGF (see Data Availability section).

Biases in this extended dataset have already been identified. The waste sector is 30% of total anthropogenic CH_4 emissions by 1850. This is likely because earlier CMIP5 data are scaled back in time with population data. This is an overestimate of anthropogenic CH_4 emissions from this source at that time since landfills and wastewater treatment plants, which create the anaerobic conditions conducive to CH_4 emissions, did not start to come into widespread use until around 1930. However, as noted in the main paper, earlier CMIP5 emission estimates did not distinguish between biomass and coal combustion. CH_4 emissions from biomass combustion are much larger than those from coal combustion, which means methane emissions from the residential sector are underestimated in this extrapolation. A rough estimate indicates that these two effects are of similar (and offsetting) magnitude. Further work is necessary to better refine historical CH_4 emissions.

A3 Sector definitions
A3.1   Combustion emissions

Fuel combustion emission sectors in CEDS are defined in reference to corresponding IEA energy statistics energy flows as given in this table. One exception is evaporative emissions from road transport, which are mapped to the 1A3b road transport sector, following general air pollutant inventory practice, even though this is a non-combustion emissions source. Also NMVOC evaporative emissions from oil tanker loading are not combustion emissions, but are categorized together with international shipping emissions.

Note that the current calibration (e.g., scaling) to country emission inventories is generally not performed at this level of detail, which means that sectoral emission values are more reliable at the aggregate sector level.

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Table A1 Sector Definitions of Combustion Emissions (IEA and NFR14 Codes)

IEA Energy Statistics	IEA Name	NFR14 Code	CEDS Working Sector Name	Aggregate Sector (Gridding)
MAINELEC	Main-Activity-Producer-Electricity-Plants	1A1a	1A1a_Electricity-public	Power_and_Heat
AUTOELEC	Autoproducer-Electricity-Plants	1A1a	1A1a_Electricity-autoproducer	Industrial_Combustion
MAINCHP	Main-Activity-Producer-CHP-Plants	1A1a	1A1a_Electricity-public	Power_and_Heat
AUTOCHP	Autoproducer-CHP-Plants	1A1a	1A1a_Electricity-autoproducer	Industrial_Combustion
MAINHEAT	Main-Activity-Producer-Heat-Plants	1A1a	1A1a_Heat-production	Power_and_Heat
AUTOHEAT	Autoproducer-Heat-Plants	1A1a	1A1a_Heat-production	Power_and_Heat
IRONSTL	Iron-and-Steel	1A2a	1A2a_Ind-Comb-Iron-steel	Industrial_Combustion
NONFERR	Non-Ferrous-Metals	1A2b	1A2b_Ind-Comb-Non-ferrous-metals	Industrial_Combustion
CHEMICAL	Chemical-and-Petrochemical	1A2c	1A2c_Ind-Comb-Chemicals	Industrial_Combustion
PAPERPRO	Paper,-Pulp-and-Print	1A2d	1A2d_Ind-Comb-Pulp-paper	Industrial_Combustion
FOODPRO	Food-and-Tobacco	1A2e	1A2e_Ind-Comb-Food-tobacco	Industrial_Combustion
NONMET	Non-Metallic-Minerals	1A2f	1A2f_Ind-Comb-Non-metalic-minerals	Industrial_Combustion
CONSTRUC	Construction	1A2g	1A2g_Ind-Comb-Construction	Industrial_Combustion
TRANSEQ	Transport-Equipment	1A2g	1A2g_Ind-Comb-transpequip	Industrial_Combustion
MACHINE	Machinery	1A2g	1A2g_Ind-Comb-machinery	Industrial_Combustion
MINING	Mining-and-Quarrying	1A2g	1A2g_Ind-Comb-mining-quarrying	Industrial_Combustion
WOODPRO	Wood-and-Wood-Products	1A2g	1A2g_Ind-Comb-wood-products	Industrial_Combustion
TEXTILES	Textile-and-Leather	1A2g	1A2g_Ind-Comb-textile-leather	Industrial_Combustion
INONSPEC	Non-specified-(Industry)	1A2g	1A2g_Ind-Comb-other	Industrial_Combustion
WORLDAV	World-Aviation-Bunkers	1A3ai	1A3ai_International-aviation	Aviation
DOMESAIR	Domestic-Aviation	1A3aii	1A3aii_Domestic-aviation	Aviation
ROAD	Road	1A3b	1A3b_Road	Road
* NA	Evaporative emissions from road transport	1A3b	1A3b_Road	Road
RAIL	Rail	1A3c	1A3c_Rail	Other_Surface_Transport
WORLDMAR	World-Marine-Bunkers	1A3di	1A3di_International-shipping	International-Shipping
* NA	Evaporative emissions from tanker loading	1A3di	1A3di_Oil_tanker_loading	International-Shipping
DOMESNAV	Domestic-Navigation	1A3dii	1A3dii_Domestic-navigation (shipping)	Other_Surface_Transport
PIPELINE	Pipeline-Transport	1A3ei	1A3eii_Other-transp	Other_Surface_Transport
TRNONSPE	Non-specified-(Transport)	1A3eii	1A3eii_Other-transp	Other_Surface_Transport
COMMPUB	Commercial-and-Public-Services	1A4a	1A4a_Commercial-institutional	Residential_Commercial_Other
RESIDENT	Residential	1A4b	1A4b_Residential	Residential_Commercial_Other

AGRICULT	Agriculture/Forestry	1A4c	1A4c_Agriculture-forestry-fishing	Residential_Commercial_Other
FISHING	Fishing	1A4c	1A4c_Agriculture-forestry-fishing	Residential_Commercial_Other
ONONSPEC	Non-specified-(Other)	1A5	1A5_Other-unspecified	Residential_Commercial_Other

A3.2 Non-combustion emissions

Non-combustion emission sectors (also generally referred to as process emissions in CEDS documentation) are defined in reference to corresponding EDGAR categories as given in this table. Note that the 1A1bc sector is actually combustion-related emissions, however this sector is processed the same as non-combustion emissions in CEDS (see Sec 2.3.2).

Table A2 Sector Definitions of Non Combustion Emissions (drawn from EDGAR Processes)

EDGAR Process Description	CEDS-Working-Sector-Name	Aggregate Sector
Fuel combustion petroleum refineries	1A1bc_Other-transformation	Industrial_Combustion
coal mines	1A1bc_Other-transformation	Industrial_Combustion
Fuel combustion BKB plants	1A1bc_Other-transformation	Industrial_Combustion
Fuel combustion blast furnaces	1A1bc_Other-transformation	Industrial_Combustion
Fuel combustion charcoal production plants	1A1bc_Other-transformation	Industrial_Combustion
Fuel combustion coal liquefaction plants	1A1bc_Other-transformation	Industrial_Combustion
Fuel combustion coke ovens	1A1bc_Other-transformation	Industrial_Combustion
Fuel combustion gasification plants for biogas	1A1bc_Other-transformation	Industrial_Combustion
Fuel combustion Liquefaction/Regasification	1A1bc_Other-transformation	Industrial_Combustion
Fuel combustion non-specified transformation	1A1bc_Other-transformation	Industrial_Combustion
Fuel combustion oil and gas extraction	1A1bc_Other-transformation	Industrial_Combustion
Fuel combustion patent fuel plants	1A1bc_Other-transformation	Industrial_Combustion
Gas works	1A1bc_Other-transformation	Industrial_Combustion
BKB plants	1B1_Fugitive-solid-fuels	Fugitive_Energy_Emissions
Fuel transformation coal liquefaction plants	1B1_Fugitive-solid-fuels	Fugitive_Energy_Emissions
Fuel transformation patent fuel plants	1B1_Fugitive-solid-fuels	Fugitive_Energy_Emissions
Production of brown coal	1B1_Fugitive-solid-fuels	Fugitive_Energy_Emissions
Production of hard coal	1B1_Fugitive-solid-fuels	Fugitive_Energy_Emissions
Production of peat	1B1_Fugitive-solid-fuels	Fugitive_Energy_Emissions
Fuel transformation charcoal production plants	1B1_Fugitive-solid-fuels	Fugitive_Energy_Emissions
Fuel transformation coke ovens	1B1_Fugitive-solid-fuels	Fugitive_Energy_Emissions
Fuel transformation in gas works	1B1_Fugitive-solid-fuels	Fugitive_Energy_Emissions
Chemical heat for electricity production	1B2_Fugitive-petr-and-gas	Fugitive_Energy_Emissions
For blended natural gas	1B2_Fugitive-petr-and-gas	Fugitive_Energy_Emissions
Fuel transformation gasification plants for biogas	1B2_Fugitive-petr-and-gas	Fugitive_Energy_Emissions
Fuel transformation Liquefaction/Regasification pl	1B2_Fugitive-petr-and-gas	Fugitive_Energy_Emissions
Gas-to-liquids (GTL) plants	1B2_Fugitive-petr-and-gas	Fugitive_Energy_Emissions
Non specified transformation activity	1B2_Fugitive-petr-and-gas	Fugitive_Energy_Emissions
Petrochemical industry	1B2_Fugitive-petr-and-gas	Fugitive_Energy_Emissions
Transformation in Gas to liquids plants	1B2_Fugitive-petr-and-gas	Fugitive_Energy_Emissions
Fuel transformation petroleum refineries	1B2_Fugitive-petr-and-gas	Fugitive_Energy_Emissions
Production of oil	1B2_Fugitive-petr-and-gas	Fugitive_Energy_Emissions
Production of gas	1B2_Fugitive-petr-and-gas	Fugitive_Energy_Emissions
Production of oil	1B2_Fugitive-petr-and-gas	Fugitive_Energy_Emissions
(None)	1B2d_Fugitive-other-energy	Fugitive_Energy_Emissions
Cement production	2A1_Cement-production	Minerals
Lime production	2A2_Lime-production	Minerals
Lime production	2A2_Lime-production	Minerals
Soda ash production and use	2Ax_Other-minerals	Minerals
Brick production	2Ax_Other-minerals	Minerals
Glass bottles	2Ax_Other-minerals	Minerals
Glass production	2Ax_Other-minerals	Minerals

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Other non-metallic minerals	2Ax_Other-minerals	Minerals
Other uses of carbonate	2Ax_Other-minerals	Minerals
Ammonia production	2B_Chemical-industry	Chemical-industry
Bulk chemicals production	2B_Chemical-industry	Chemical-industry
Nitric acid production	2B_Chemical-industry	Chemical-industry
Adipic acid production	2B_Chemical-industry	Chemical-industry
Silicon carbide production	2B_Chemical-industry	Chemical-industry
Calcium carbide production	2B_Chemical-industry	Chemical-industry
Bulk chemicals production	2B_Chemical-industry	Chemical-industry
Caprolactam production	2B_Chemical-industry	Chemical-industry
Bulk chemicals production	2B_Chemical-industry	Chemical-industry
N-fertilizer production	2B_Chemical-industry	Chemical-industry
Specialities production	2B_Chemical-industry	Chemical-industry
Sulphuric acid production	2B_Chemical-industry	Chemical-industry
Titanium oxide production	2B_Chemical-industry	Chemical-industry
Bulk chemicals production	2B_Chemical-industry	Chemical-industry
Glyoxal production	2B_Chemical-industry	Chemical-industry
Glyoxylic acid production	2B_Chemical-industry	Chemical-industry
Crude steel production	2C_Metal-production	Metals-industry
Blast furnaces	2C_Metal-production	Metals-industry
Pig iron production	2C_Metal-production	Metals-industry
Sinter production	2C_Metal-production	Metals-industry
Pellet production	2C_Metal-production	Metals-industry
Steel casting	2C_Metal-production	Metals-industry
Ferro Alloy production	2C_Metal-production	Metals-industry
Aluminium production	2C_Metal-production	Metals-industry
Magnesium production	2C_Metal-production	Metals-industry
Aluminium production	2C_Metal-production	Metals-industry
Other non-ferrous production	2C_Metal-production	Metals-industry
Gold production	2C_Metal-production	Metals-industry
Copper production	2C_Metal-production	Metals-industry
Mercury production	2C_Metal-production	Metals-industry
Other non-ferrous production	2C_Metal-production	Metals-industry
Lead production	2C_Metal-production	Metals-industry
Other non-ferrous production	2C_Metal-production	Metals-industry
Magnesium production	2C_Metal-production	Metals-industry
Zinc production	2C_Metal-production	Metals-industry
Paper production	2H_Pulp-and-paper-food-beverage-	Pulp-and-paper-food-
Wood pulp production	2H_Pulp-and-paper-food-beverage-	Pulp-and-paper-food-
Beer production	2H_Pulp-and-paper-food-beverage-	Pulp-and-paper-food-
Bread production	2H_Pulp-and-paper-food-beverage-	Pulp-and-paper-food-
Other food production	2H_Pulp-and-paper-food-beverage-	Pulp-and-paper-food-
Wine production	2H_Pulp-and-paper-food-beverage-	Pulp-and-paper-food-
Non energy use in petrochemical industry	2L_Other-process-emissions*	Other_Non-Combustion
Non energy use in industry, transformation industr	2L_Other-process-emissions*	Other_Non-Combustion
Non energy use in transport sector	2L_Other-process-emissions*	Other_Non-Combustion
Other non energy use	2L_Other-process-emissions*	Other_Non-Combustion
Non energy use in petrochemical industry	2L_Other-process-emissions*	Other_Non-Combustion
Non energy use in industry, transformation industr	2L_Other-process-emissions*	Other_Non-Combustion
Non energy use in transport sector	2L_Other-process-emissions*	Other_Non-Combustion
Other non energy use	2L_Other-process-emissions*	Other_Non-Combustion
Other non-combustion not elsewhere (NOT	2L_Other-process-emissions*	Other_Non-Combustion
Solvents in glues and adhesives	2D_Paint-application	Solvents
Solvents in graphic arts	2D_Paint-application	Solvents
Solvents in paint	2D_Paint-application	Solvents
Solvents in dry cleaning	2D_Degreasing-Cleaning	Solvents
Solvents in households products	2D_Degreasing-Cleaning	Solvents
Solvents in industrial degreasing	2D_Degreasing-Cleaning	Solvents
Solvents in chemical industry	2D_Chemical-products-manufacture-processing	Solvents
Other solvents use	2D_Other-product-use	Solvents
Prodcution and use of other products	2D_Other-product-use	Solvents
Use of N2O as anesthesia	2D_Other-product-use	Solvents

Solvents in leather production	2D_Other-product-use	Solvents
Solvents in pesticides	2D_Other-product-use	Solvents
Solvents in rubber and plastics industry	2D_Other-product-use	Solvents
Solvents in vegetative oil extraction	2D_Other-product-use	Solvents
Enteric fermentation by cattle	3E_Enteric-fermentation	Agriculture_non-combustion
Enteric fermentation by buffalo	3E_Enteric-fermentation	Agriculture_non-combustion
Enteric fermentation by sheep	3E_Enteric-fermentation	Agriculture_non-combustion
Enteric fermentation by goats	3E_Enteric-fermentation	Agriculture_non-combustion
Enteric fermentation by camels	3E_Enteric-fermentation	Agriculture_non-combustion
Enteric fermentation by horses	3E_Enteric-fermentation	Agriculture_non-combustion
Enteric fermentation by asses	3E_Enteric-fermentation	Agriculture_non-combustion
Enteric fermentation by swine	3E_Enteric-fermentation	Agriculture_non-combustion
Manure management of cattle	3B_Manure-management	Agriculture_non-combustion
Manure management of buffalo	3B_Manure-management	Agriculture_non-combustion
Manure management of sheep	3B_Manure-management	Agriculture_non-combustion
Manure management of geese	3B_Manure-management	Agriculture_non-combustion
Manure management of goats	3B_Manure-management	Agriculture_non-combustion
Manure management of camels	3B_Manure-management	Agriculture_non-combustion
Manure management of horses	3B_Manure-management	Agriculture_non-combustion
Manure management of assess	3B_Manure-management	Agriculture_non-combustion
Manure management of swine	3B_Manure-management	Agriculture_non-combustion
Manure management of chicken	3B_Manure-management	Agriculture_non-combustion
Manure management of ducks	3B_Manure-management	Agriculture_non-combustion
Manure management of turkey	3B_Manure-management	Agriculture_non-combustion
Separate category for Rice CH4 emissions (not in	3D_Rice-Cultivation	Agriculture_non-combustion
Agricultural soils, rice cultivation	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, nitrogen fertilizers	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, animal waste as fertiliser	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, N-fixing crops	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, crop residues	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, histosols	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, buffalos in pasture	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, camels in pasture	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, cattle in pasture	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, chicken in pasture	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, ducks in pasture	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, goats in pasture	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, horses in pasture	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, mules and asses in pasture	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, pigs in pasture	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, sheep in pasture	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, turkeys in pasture	3D_Soil-emissions	Agriculture_non-combustion
Indirect N2O emissions	3D_Soil-emissions	Agriculture_non-combustion
Indirect N2O emissions - deposition, other	3D_Soil-emissions	Agriculture_non-combustion
Indirect N2O emissions - deposition, agriculture	3D_Soil-emissions	Agriculture_non-combustion
Indirect N2O emissions - leaching and runoff	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, CO2 from urea fertilization	3D_Soil-emissions	Agriculture_non-combustion
Agricultural soils, liming	3D_Soil-emissions	Agriculture_non-combustion
Solid waste disposal (landfills)	5A_Solid-waste-disposal	Waste
Industrial waste water	5D_Wastewater-handling	Waste
Domestic waste water	5D_Wastewater-handling	Waste
Human Waste (not in EDGAR)	5D_Wastewater-handling	Waste
Solid waste disposal (incineration)	5C_Waste-combustion	Waste
Residential waste combustion (not in EDGAR)	5C_Waste-combustion	Waste
Other waste handling	5E_Other-waste-handling	Waste
Coal fires underground	7A_Fossil-fuel-fires	Fosil_Fuel_Files
Oil fires	7A_Fossil-fuel-fires	Fosil_Fuel_Files
Gas fires	7A_Fossil-fuel-fires	Fosil_Fuel_Files

1450   * This sector is currently equal to zero in all years and countries, and not included in data files.

A4 Fuel mapping to IEA products

CEDS Fuel	IEA Product

biomass	Industrial waste (TJ-net) Municipal waste (renewable) (TJ-net) Municipal waste (non-renewable) (TJ-net)	Primary solid biofuels (TJ-net) Non-specified primary biofuels/waste (TJ-net) Charcoal (kt)
brown_coal	Brown coal (if no detail) (kt) Lignite (kt)	Peat (kt) Peat products (kt)
coal_coke	Coke oven coke (kt)	
hard_coal	Hard coal (if no detail) (kt) Anthracite (kt) Coking coal (kt) Other bituminous coal (kt) Sub-bituminous coal (kt)	Patent fuel (kt) Gas coke (kt) Coal tar (kt) BKB (kt)
light_oil	Refinery feedstocks (kt) Additives/blending components (kt) Other hydrocarbons (kt) Ethane (kt) Liquefied petroleum gases (LPG) (kt) Motor gasoline excl. biofuels (kt) Aviation gasoline (kt) Gasoline type jet fuel (kt)	Kerosene type jet fuel excl. biofuels (kt) Other kerosene (kt) Other Kerosene (kt) Naphtha (kt) White spirit & SBP (kt) Biogasoline (kt) Other liquid biofuels (kt)
diesel_oil	Natural gas liquids (kt) Gas/diesel oil excl. biofuels (kt)	Lubricants (kt) Biodiesels (kt)
heavy_oil	Oil shale and oil sands (kt) Crude/NGL/feedstocks (if no detail) (kt) Crude oil (kt) Fuel oil (kt)	Bitumen (kt) Paraffin waxes (kt) Petroleum coke (kt) Other oil products (kt)
natural_gas	Gas works gas (TJ-gross) Coke oven gas (TJ-gross) Blast furnace gas (TJ-gross) Other recovered gases (TJ-gross)	Natural gas (TJ-gross) Natural Gas (TJ-gross) Refinery gas (kt) Biogases (TJ-net)
NOT MAPPED	Elec/heat output from non-specified manufactured gases Heat output from non-specified combustible fuels Nuclear Hydro Geothermal (direct use in TJ-net) Solar photovoltaics Solar thermal (direct use in TJ-net) Tide, wave and ocean	Wind Other sources Electricity (GWh) Heat (TJ) Total Total of all energy sources Memo: Renewables Heat from chemical sources Electric boilers Heat pumps

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* Spatial proxy data within each country is held constant before and after the years shown. See Supplement for further details on the gridding proxy data including definitions for the EDGAR gridding codes in this table.