Supplemental Data and Assumptions

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

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Rachel M. Hoesly
Steven J. Smith
Leyang Feng
Zbigniew Klimont
Greet Janssens-Maenhout
Tyler Pitkanen
Jonathan J. Seibert
Linh Vu
Robert J. Andres
Ryan M. Bolt
Tami C. Bond
Laura Dawidowski
Nazar Kholod
Jun-ichi Kurokawa
Meng Li
Liang Liu
Zifeng Lu
Maria Cecilia P. Moura
Patrick R. O'Rourke
Qiang Zhang

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1. Introduction

The Community Emissions Data System (CEDS) uses a variety of data, from population and energy statistics to emissions inventories and a variety of auxiliary data. The journal paper (Hoesly et al. 2017) provides a general overview of the methodologies and data sources used. This document provides additional detail on methods and assumptions used for production of the CEDS MIP6 historical emissions data release.

Note that, for convenience, CEDS refers to countries, which are geographical and statistical entities for which relevant data are available (e.g., population, energy consumption, emission inventories, etc.). No implications for the political status of any entity is implied by this designation.

2. General Input and Non-Energy Activity Data

2.1. Population

Population is a foundational data input and some components of the CEDS system requires population data for all countries. We, therefore, generate a full population time series for each country. Population is used as a default driver for non-combustion emissions so that a continuous time series is available for all countries. This enables smooth interpolation and extension of data values.

Population inputs for CEDS include total population and urban population shares for the period 1700-2100, so that total, urban, and rural population estimates are available for all countries. Data to 2100 are estimated so that population data is continuous and available for all years. Because CEDS estimates emissions out to the most recent full year, population data for the most recent CEDS years may be from projections rather than historical estimates. While data beyond the present year is not used in CEDS, these data are is available for comparison with other future projections.

Three sources were used to estimate population levels: the United Nations (UN), World Bank (WB), and the History Database of the Global Environment (HYDE) population statistics. Generally, UN/WB estimates were used for post-1950 periods and HYDE historical estimates were used for earlier periods.

2.1.1. Data Sources

Three sources were used to generate CEDS population inputs:

UN population statistics provides total population for 1950-2100 and urban population shares for 1950-2050, with several future projection scenarios. UN population were downloaded from:

- http://esa.un.org/unpd/wpp/DVD/
- http://esa.un.org/unpd/wup/CD-ROM/

WB population statistics provides total population and urban population shares for 1960-2014.

WB population input can be pulled from the World Development Indicators (WDI) API using the R package “FAOSTAT”.

HYDE population statistics provides total population and urban population shares for 1700-2030, with 1700-1950 data available every 10 years. HYDE population input is currently stored as a file in the local directory.

2.1.2. Calculation Details

Pre-processing

UN urban population shares for 2051-2100 were linearly extrapolated from 2050 share and 2049-2050 growth rate. HYDE 1700-1950 data (originally available every 10 years) were linearly interpolated for all years in between.

Merging

The general rule is to use UN/WB estimates for post-1950 periods, and merge to HYDE historical estimates for earlier periods.

For 1950-2100, UN data (population and urban shares) were used whenever possible. For countries without UN data, WB data were substituted for 1960-2014 and extrapolated for 1950-2100 using the trend of a proxy country. This routine is currently used to generate Kosovo’s population with Serbia as the proxy; since Kosovo has no UN or WB urban shares data, it is assumed to have Serbia’s UN urban population shares for all years.

For 1901-1949, the difference between 1950 UN/WB and Hyde values were linearly interpolated to converge to HYDE in 1900:

```
UN_WB(year) = HYDE(year) + [ UN_WB(1950) - HYDE(1950) ] * (year - 1900) / (1950 - 1900)
```

For 1700-1900, HYDE data were used whenever possible. For countries without HYDE data, 1950 UN/WB data were extrapolated backwards using HYDE year-to-year trends of a proxy country. This routine is currently used to generate population for the following countries:

- Curacao, Sint Maarten, Caribbean Netherlands: use Netherlands Antilles as proxy
- Montenegro, Serbia, Kosovo: use Serbia and Montenegro as proxy
- South Sudan: use Sudan as proxy
- Mayotte: use Comoros as proxy

Finally, population for dissolved countries were generated by summing constituent countries' population. Population for both dissolved and constituent countries were kept in the database. This routine is currently used to generate population for the following countries:

- Czechoslovakia = Czech + Slovakia
- Serbia and Montenegro = Serbia + Montenegro

- Netherlands Antilles = Aruba + Curacao + Sint Maarten
- Belgium-Luxembourg = Belgium + Luxembourg

2.2. Pulp and Paper Consumption

The main data source is FAO Forestry Statistics, which provides 1961-2014 wood pulp production, imports and exports. FAO Statistics can be pulled from the FAO API using the R package “FAOSTAT”.

Since original FAO data are scattered and not smooth, and we are using this data as a proxy for combustible waste generation, we employ several layers of discontinuity correction.

To correct for gaps in FAO inputs, missing years are linearly interpolated for production. For imports/exports, missing years are first scaled with population, then replaced with the 4-year running average.

Wood pulp consumption is then derived as

```
Consumption = Production + Imports - Exports
```

To smooth out bumps, we replace per-capita consumption with the LOESS (local regression) value. Most countries use regional average per-capita consumption, except China, India, Brazil, Mexico, South Africa, and Egypt. Data before 1999 for FSU countries are discarded to avoid a large jump in 1994-1995 consumption. For years with missing data, the per-capita value of the nearest available year is carried over. This step produces a time series for 1961-2014 pulp and paper consumption.

To extend to 1750, 1961 pulp and paper consumption is scaled back in time as a constant per-capita value. (Note that emissions from this sector do not extend back to 1750; the emission factors for this sector are assumed to decline to zero as specified in the historical extension.)

2.3. Metal Smelting

Non-Ferrous metal smelting is a source of SO_2 emissions. Smelter production of copper, zinc, lead, and nickel were complied from USGS Minerals statistics (https://minerals.usgs.gov/minerals/pubs/commodity/), with data from 1850-1990 from sources as cited in Smith et al. (2011). Sulfur emissions were estimated by multiplying default emissions factors for each metal to get total potential non-ferrous sulfur emissions and subtracting sulfur in acid production (converted to a smoothed removal percentage given the somewhat coarse reporting for sulfur removals), also from USGS mineral yearbooks. Emission factors and removal percentages were adjusted where needed to better match published country level inventory data. These default time series for SO_2 emissions are then used as the driver data for SO_2 emissions from metal smelting.

China removal percentages for recent years were estimated using data from (Wu etal 2012) on the fraction of smelters with acid plants. Kazakhstan smelting estimates were adjusted to be consistent with SO_2 emissions over 2005 - 2014 from annual reports from Kazakhmys (and its successor company KAZ Minerals), which is the dominant copper producer in Kazakhstan, and had substantially reduced emissions over that period.

SO_2 emissions from pig iron production are predominately from fossil fuels used in this process, and would therefore be accounted for as part of the fuel combustion sector. There are several documented exceptions, however, where high sulfur-ores have been used in iron ore sintering plants. Two of these are currently included in the CEDS default, and are added to the non-Ferrous metal smelting emissions estimates discussed above.

One is the Raahe sintering plant in Finland (whose feedstock is high sulfur ore from Kostomuksha mine in Russia, particularly before the mid-1980s). Emissions as reported in company (Rautaruukki and predecessor companies) reports for 1980 and 1990 forward were linearly interpolated between 1980 and 1990 and scaled with finish pig iron production before 1980 back to opening of plant in 1960.

A second example is the Algoma Steel Corporation Ltd. sintering plant in Wawa, Ontario. SO_2 emissions over 1939 to 1996 are taken from Rowe (1999).

The early US inventory data that are used in CEDS include SO_2 emissions from iron sintering in the metal smelting category. In order to consistently account for these emissions we have also added these estimates to the metal smelting category, even though these emissions arise from fuels used in the sintering process.

2.4. Pig Iron Production

Pig iron production is currently used as an emissions factor driver for metal production CO (e.g. iron production) and other transformation BCOC (e.g. coke production). Note that BCOC emissions from coke production are scaled to match SPEW values, so that this driver is only used to interpolate the SPEW 5-year values to annual values.

Pig iron production data are derived from multiple sources.

1980-2014: https://www.worldsteel.org/

USA 1799-1970 pig iron production comes from estimates from U.S. Department of Commerce - The Bureau of the Census (1975), Pig Iron Shipments 1799 - 1970.

Europe 1780-1970 pig iron production comes from Mitchell, B.R. (1998c). International historical statistics: Europe, 1750-1993.

For previous years, the SPEW database provides global pig iron production from 1850-2014 (Bond et al. 2007). The following sources were used to generate SPEW data:

- USA 1910-2014: USGS
- Other regions 1910-1979: extrapolated to match USGS world totals.

Values for missing years are interpolated, and production for disaggregated countries is split on population. Countries with all zero production from 1750-1970 are removed. The resulting dataset provides 1750-1975 pig iron production by country.

2.5. Activity Drivers for Non-Combustion Sectors

The following table shows the activity drivers for non-combustion sectors:

Table 1. Non-Combustion Activity Drivers

Sector	Activity Driver
1A1bc_Other-transformation	population
1A3di_Oil_Tanker_Loading	population
1B1_Fugitive-solid-fuels	population
1B2_Fugitive-petr-and-gas	Refinery and Natural Gas Production
1B2d_Fugitive-other-energy	Refinery and Natural Gas Production
2A1_Cement-production	population
2A2_Lime-production	population
2Ax_Other-minerals	population
2B_Chemical-industry	2C_Metal-production
population	2D_Degreasing-Cleaning
CDIAC liquid fuels	2D_Paint-application
CDIAC liquid fuels	2D_Chemical-products-manufacture-processing
2D_Other-product-use	population
2H_Pulp-and-paper-food-beverage-wood	population
3B_Manure-management	population
3D_Rice-Cultivation	population
3D_Soil-emissions	population
3E_Enteric-fermentation	population
3F_Agricultural-residue-burning-on-fields	population
3I_Agriculture-other	population
5A_Solid-waste-disposal	population
5D_Wastewater-handling	population
5E_Other-waste-handling	population
5C_Waste-combustion	Pulp and Paper Consumption
6A_Other-in-total	population
6B_Other-not-in-total	population
7A_Fossil-fuel-fires	population

3. Energy Consumption Data

3.1. IEA Energy Statistics

The central energy dataset is the IEA energy statistics. The full IEA dataset, along with fuel heat contents, are converted to .csv files and processed as a central portion of the CEDS system. This data needs to be purchased from the IEA (both OECD and non-OECD) if a user would like to run the CEDS data system. See: http://www.iea.org/statistics/.

3.1.1. Disaggregating Countries/Regions

Composite Regions (Other Africa, Other Asia, etc) within the IEA data are disaggregated using population data. While CDIAC data could be used to better disaggregate fuel use for these countries, some included in IEA aggregate regions are not included in the CDIAC data. Disaggregation of IEA composite regions is as follows:

Other Africa

Burundi, Burkina Faso, Central African Republic, Comoros, Cape Verde, Djibouti, Western Sahara, Guinea, Gambia, Guinea-Bissau, Equatorial Guinea, Liberia, Lesotho, Madagascar, Mali, Mauritania, Malawi, Reunion, Rwanda, Sierra Leone, Somalia, Sao Tome and Principe, Swaziland, Seychelles, Chad, and Uganda

Other Non-OECD Americas

Aruba, American Samoa, Antigua and Barbuda, Bahamas, Belize, Bermuda, Barbados, Cayman Islands, Dominica, Falkland Islands, Guadeloupe, Grenada, French Guiana, Guyana, Saint Kitts and Nevis, Saint Lucia, Montserrat, Martinique, Puerto Rico, Saint Pierre and Miquelon, Suriname, Sint Maarten, Turks and Caicos Islands, Saint Vincent And Grenadines, British Virgin Islands, United States Virgin Islands

Other Asia

Afghanistan, Bhutan, Cook Islands, Fiji, Federated States of Micronesia, Kiribati, Laos, Macao, Maldives, Marshall Islands, New Caledonia, Niue ,Palau, Papua New Guinea, French Polynesia, Soloman Islands, Tokelau, Timor-Leste, Tongo, Vanuatu, Wallis and Futuna Islands, and Samoa

Gridded data reflect the aggregation of the above regions with population. Aggregate emissions results for these countries, provided as a supplement to this article are released at the IEA aggregate region level. Disaggregate emissions results are available upon request.

3.2. BP Energy Statistics

BP energy statistics are used to extend the IEA energy data up to the most recent full year contained in the BP statistics. For each BP country and region, CEDS total consumption (default from IEA) for each fossil fuel category (coal, petroleum, and natural gas) is scaled by fuel. This extends the IEA energy statistics so that total fossil-fuel consumption is increased or decreased following the BP trend. The sectoral composition of consumption is not changed.

BP data is also used to reconstruct Former Soviet Union energy data (detailed in this supplement in Section 3.5).

3.3. Earlier Fossil Energy Consumption

For years before IEA data are available, total coal, gas, and petroleum energy consumption was extrapolated back in time using CDIAC CO_2 emissions, corrected to better match historical consumption estimates (Andres et al. 1999 from 1751 to 1950, UN after 1950). 1750 values were taken to be equal to 1751 values. Sector splits were taken from IEA data (after 1960 for OECD countries, and 1971 for other countries), and these were extrapolated back in time such that the sector splits were equal to the SPEW model (Bond et al. 2007) splits by 1900.

3.4. Biomass

Statistics for biomass use are uncertain and inconsistent over time. Given its importance for a number of emission species, we focused on residential biomass consumption. For this project we merged a number of data sources to construct a biomass consumption time series. The primary datasets used are the IEA energy statistics and a historical reconstruction described in Fernandes et al. 2007. The principles behind the construction of the time series are:

- To provide priority to the IEA data since this may be data more directly reported by countries
- Assume that sudden drops in biomass consumption going back in time are not real and are due, instead, to data gaps
- Merge to the Fernandes et al. historical estimate for earlier time periods.

3.4.1. Data Sources

Four sources were used to generate residential biomass consumption for CEDS:

IEA energy statistics provides 1960-2013 residential biomass consumption (1970 or later for non-OECD countries) in energy units by country and fuel type. Note that IEA energy statistics is proprietary data and must be purchased. For more details, see the CEDS Wiki User_Guide.

Fernandes et al. (2007) provides 1850-2000 residential biomass consumption by country and fuel type.

Denier van der Gon et al. (2015) provides 2005 residential biomass consumption for 42 European countries.

EIA Monthly Energy Review, *Table 10.2a Renewable energy - Consumption: residential and commercial sectors* provides 1949-2014 U.S. residential biomass consumption by fuel type. http://www.eia.gov/totalenergy/data/monthly/#renewable.

3.4.2. Calculation Details

Overall, biomass time series were converted to per-capita values using rural population when conducting interpolation and gap filling, since biomass consumption tends to be dominated by rural population. Where reported statistics are available, this assumption has no impact on the results.

Processing Fernandes data

We first produced 1850-2013 time series of residential biomass consumption by country and fuel type from Fernandes et al. biofuels data. Note that most of the following estimates/corrections to the original dataset were done on a rural per-capita basis. While urban areas also consume biomass, rural areas generally dominate biomass consumption totals. By trending (where data is not otherwise available) with rural population we hope to broadly capture the impact of urbanization trends in each country.

For CEDS countries without Fernandes data, the rural per-capita value of a proxy country was used. For dissolved countries, the composite country (before dissolution) was used as proxy for constituent members. For details on the proxy country mapping, see *input/mappings/Fernandes_proxy_country_mapping.csv*.

For 1850-1900, we assumed a minimum of 0.25 kt/rural population in domestic total fuelwood consumption. This minimum was phased in from 1900 to 1940 (so that this minimum equals 0 in 1940). This minimum represents biomass fuel used for cooking, which would be the case in all regions. Regions with heating requirements would be assumed to have higher per-capita biomass fuel demand.

To correct for discontinuities, if rural per-capita biomass for one year was zero or drops substantially (below a pre-specified threshold relative to the next year), its value was replaced with the next non-zero value.

Finally, the last (most recent) non-zero rural per-capita biomass value for each country was carried forward in time.

Correcting discontinuities in IEA

We also produced a 1960-2013 time series of residential biomass consumption using the IEA data using the following procedure to detect and correct gaps in IEA biomass consumption. Gaps may include missing (zero) biomass consumption and sudden increases/decreases in year-to-year consumption. Note that the procedure was done on a rural per-capita consumption basis.

To fix missing biomass, we went backwards in time and extrapolated missing IEA using the IEA/Fernandes ratio of the average of the 3 years immediately following the break. Results may be cascaded if needed.

To fix sudden increases/decreases, we looked for the most recent year where IEA year-to-year ratio exceeds a pre-specified threshold. Biomass for this year and all earlier years were extrapolated backwards using 3-year-average IEA/Fernandes ratio trends.

Finally, to keep extrapolated IEA values from becoming unrealistically large, we applied a per-capita upper bound taken to be the maximum of IEA and Fernandes average for 1969-1971 and for the 3 years immediately following the most recent gap.

Merging

The general rule was to prioritize IEA data and merge to Fernandes historical estimates for earlier periods. Adjustments may be made if IEA data differ significantly from other sources.

IEA data were replaced with trends from EIA for the United States.

For countries with Denier van der Gon et al. (European) data and where 2005 IEA and European data differ significantly, either IEA or Fernandes data was used on a case-by-case basis.

For the remaining countries, IEA data was used, unless IEA was significantly and consistently smaller than Fernandes (below a pre-specified threshold, for N years in a row), in which case Fernandes was used.

This step produced our residential biomass series for 1960-2013.

Extending to 1700

Historical Fernandes data were used to extend the residential biomass series back to 1700. For countries using IEA data for 1960-2013, IEA was interpolated so that the rural per-capita value converges to Fernandes by 1920. The calculation details are outlined in the following paragraphs.

For 1850-1920, Fernandes rural per-capita values were used.

For 1700-1849, Fernandes 1850 rural per-capita value was carried backward (kept constant).

For 1921-2013, Fernandes values were used for countries where we also used Fernandes values for 1960-2013. For countries using IEA for 1960-2013, we defined a split year to be the most recent year where extrapolated/adjusted IEA falls below Fernandes, if applicable, and 1960 otherwise. IEA at split year was interpolated so that the rural per-capita value matches Fernandes in 1920. The interpolated values were adjusted to never dip below IEA at split year or Fernandes of the same year, whichever is smaller.

This step produced residential biomass series for 1700-2013.

Correcting double counting in unspecified biomass

Reported IEA residential and the unspecified biomass category were sometimes correlated (i.e. one drops as the other rises). For places where residential and unspecified biomass were correlated, an adjustment was made such that the estimated residential biomass value was subtracted from unspecified biomass to avoid double counting.

3.4.3. Known Issues

One of the main purposes of our processing routine is to smooth out sudden jumps in residential biomass consumption. This is not always possible, however, due to the difficulty in reconciling multiple datasets, discontinuities in the population data used, choices of threshold values, and the inconsistent nature of biomass statistics. Examples of known discontinuities in our final biomass series include: India 1945, Ukraine 1913, Bangladesh 1945, North Korea 1939, South Korea 1949 and 1966. Some of these discontinuities may reflect historical events, while others may be data artifacts. We welcome input from regional experts to improve these time series.

3.5. Former Soviet Union Energy Use

Historical energy data in the Former Soviet Union are subject to discontinuities. Many of these stem from the abrupt changes in reporting protocol, so while aggregate Former Soviet Union data may be continuous, energy data disaggregated to countries and sectors is not.

To maintain continuity, Former Soviet Union energy use is disaggregated to countries and sectors using smoothed fuel and sector shares. Total USSR aggregate fuel use is disaggregated to country fuel use using BP energy statistics. Country fuel use is disaggregated to sectors using sector shares derived from IEA energy statics. Effort was made to smooth these of these sector shares. This process was largely subjective and tailored to each country based on the data.

3.6. Shipping Fuel

Reported shipping fuel consumption is typically underestimated in global energy statistics, particularly for international shipping (also termed "bunker fuels") (IMO 2014). For this reason, our shipping fuel consumption estimate is based on a composite time series from several sources from 1850-2012, based on bottom-up estimates over recent years (IMO 2014, Endresen et al. 2007, Eyring et al. 2010, Fletcher 1997, Fouquet and Pearson 1998, Smith et al. 2011). Petroleum-based fuels are split between diesel and heavy oil following Smith et al. (2011).

Within CEDS we subtract total shipping fuel reported by IEA (domestic navigation, international bunkers, and fishing) from the total exogenous fuel time series and place this difference into the global shipping sector, recognizing that some of this difference could actually be domestic navigation in some regions. Where IEA shipping heavy oil is above exogenous data, the difference is subtracted from global international shipping diesel oil. Before the start of the IEA data in 1960, the exogenous shipping fuel estimate is assigned to the global international shipping sector.

In summary, where bunker fuel data exists in the IEA database this is left in place, and any difference between the total from all countries of shipping fuels in IEA and the exogenous global total developed above is place in the "global" region. Because the country fuel values have little geographical relevance (e.g., the fuel is consumed over some international route), international shipping emissions are summed and reported only at the global level.

The difference between the bottom-up estimates and reported IEA data is smaller in recent years. To extend shipping fuel estimates to 2014 we keep the correction to the IEA totals constant.

Shipping fuel shifts to coal in earlier years (see Smith et al. 2011). Before 1855, global and British shipping coal are interpolated from Fouquet and Pearson 1998 estimates, then extrapolated assuming zero 1750 shipping fuel.

4. Emissions Inventories

4.1. CDIAC - Historical CO_2 Emissions

Many CEDS emission estimates are extended back to 1750 using CDIAC historical CO_2 emissions, which estimate CO_2 emissions from fossil fuels by country from 1751 – 2011 by solid, liquid and gas fuels, cement, bunker and flaring emissions. This implicitly assumes that the CO_2 emissions are proportional to fuel use. In a couple countries, this extrapolation is corrected to better match historical trends. (The latest CDIAC emissions to 2013 were released after production of the CEDS data for CMIP6. The CEDS system will be updated to use this latest released in the future.)

4.1.1. Historical Country Disaggregation

Unless otherwise noted, emissions are disaggregated using emissions split of disaggregate countries, averaged over the first 2 years of available disaggregate data, which are trended back in time using population splits, which are then renormalized to 1.

FSU (Former Soviet Union) is disaggregated before 1991 to the following iso codes: aze, arm , blr, est, geo, kaz, kgz, lva, ltu, mda, tjk, tkm, ukr, uzb, rus

Former Yugoslavia is disaggregated before 1991 to the following iso codes: bih, hrv, mkd, svn, scg

Czechoslovakia is disaggregated before 1991 to the following iso codes: cze, svk

East West Pakistan is disaggregated before 1971 to the following iso codes: pak, bgd

United Korea is disaggregated before 1944 using average emissions splits over 1948-1949 to the following iso codes: prk, kor

French Equatorial Africa is disaggregated before 1958 to the following iso codes: caf, cog, gab, tcd

French West Africa is disaggregated before 1957 to the following iso codes: mrt, sen, mli, gin, civ, bfa, ben, ner

Rwanda Urundi is disaggregated before 1961 to the following iso codes: rwa, bdi

Netherland Antilles and Aruba is disaggregated 1926-1985 to the following iso codes: ant, abw

Netherland Antilles is disaggregated before 2011 using only population splits to the following iso codes: cuw, sxm

Rhodesia Nyasaland is disaggregated before 1963 to the following iso codes: zmb, mwi

Leeward Islands is disaggregated from 1950 - 1956 to the following iso codes: kna, atg

4.1.2. Corrections

Original CDIAC liquid fuel emissions for the following countries before 1952 are discontinuous: - ISO codes: abw, arg, bhr, cuw, tto, irn, ven, brn, kwt

For the countries listed above, CDIAC liquid fuel emissions are linearly interpolated between first non zero data point and 1952. These discontinuities are likely from changes in data collection over those years and throughout CEDS processing, lead to large emission spikes in final CEDS estimates. The fossil fuel estimates used in CDIAC before 1950 are apparent consumption, which is production minus net exports. If export data is not available or incomplete, this can lead to a spike in apparent consumption.

Additionally, the following data points years were smoothed over:

- kwt: 1960-1969

- sau: 1947
- irn: 1953
- irq: 1949-1955
- mex: 1912-1938

The difference between smoothed CDIAC liquid fuel emissions and original CDIAC liquid fuel emissions from 1908 -1946 represent up to 3% of total global CO_2 emissions (originally reported by CDIAC) and 4-5% in 1947 and 1948.

4.2. Detailed Inventories

These inventories provide emissions by fuel and sector (and for GAINS and SPEW fuel consumption, NEI provides CO_2 for mobile sectors). This means that emission factors for combustion sources can be estimated using these data and used as default emission factors in CEDS.

4.2.1. GAINS

As detailed in other sections, global emission factors from the GAINS model for the years 2000, 2005, 2010, and 2020 were used as default values, and also to extrapolate trends in emission factors for recent years beyond where emission factors were available. The dataset used here is the ECLIPSE_V5a "current legislation" (CLE) base case (Stohl et al., 2015, Klimont et al., 2016).

The GAINS CLE case assumes legislation currently "on the books" is implemented. This is particularly relevant for extrapolation after 2010, because 2010 is an estimate of actual emissions at that point in time. This could under-estimate emissions in cases of less than full implementation. The reverse could also be the case, but is somewhat less likely given the short timeframe over which we are using these data.

4.2.2. SPEW

The Speciated Pollutant Emissions Wizard (SPEW) is a historical inventory of BC and OC emissions developed by Bond et al. (2007). It contains emissions and associated energy use for technologies and countries/regions for 1850 - 2000. SPEW is used as the primary source for BC and OC emissions in CEDS.

4.2.3. US NEI

The United States National Emissions Inventory (USNEI) (US EPA 2013) is only used to estimate base emission factors for NH_3 The US EPA Emission Trends data at the Tier 1 level is used to calibrate emissions.

4.3. Multi Country Aggregate Inventories

These inventory data are provided at the sector level (although REAS provides data by sector and fuel, we did not make use of this additional detail). These data, are used to calibrate (e.g. scale) the CEDS estimates during the time period over which these inventory data are available.

4.3.1. EDGAR

The Emissions Database for Global Atmospheric Research (EDGAR) version 4.3 (EC-JRC/PBL 2016) gives independent emissions estimates (both aggregate and gridded) of anthropogenic air pollutants and greenhouse gasses from 1970 - 2010. EDGAR is used as the primary scaling inventory as well as gridding data proxies (detailed below).

4.3.2. UNFCCC

Many country submit national inventories to the United Nations Framework Convention on Climate Change (UNFCCC) (2015). CEDS only uses a few of these for scaling purposes: Greece, New Zealand, and Belarus.

4.3.3. EMEP

The European Monitoring and Evaluation Programme (EMEP) collects emissions from European nations.

4.3.4. REAS

Regional Emission inventory in ASia (REAS) give estimates for major air pollutants and greenhouse gasses in Asia (Kurokawa et al. 2013).

4.4. Individual Country Inventories

These are additional data for specific countries. These data are also used to calibrate (e.g. scale) the CEDS estimates during the time period over which these inventory data are available. Where data here overlaps in scope with the multi-country inventories above, the data below is given priority.

4.4.1. USA

(US EPA 2015)

4.4.2. Canada

(Environment Canada 2013)

4.4.3. Argentina

UNFCCC (2016) ==== Australia

Australian Department of the Environment (2016) ==== China (Li et al., 2017)

4.4.4. Korea

South Korea National Institute of Environmental Research 2016

4.4.5. Taiwan

The emissions inventory for Taiwan is available for year 2003, 2006 and 2010. The data sources for year 2003 and year 2006 are Taiwan EPA Report EPA-95-FA11-03-D067 and Taiwan EPA Report EPA-96-FA11-03-A174, respectively. The data source for year 2010 is Taiwan Emissions Data System (TEDS version 8.1)

4.4.6. Japan

Preliminary update of Kurokawa et al., (2013b)

5. Default Combustion Emission Factors

Default emission factors serve as a starting place to create emissions estimates for scaling. While many emissions estimates are scaled to inventories (by scaling the emission factors), some default emissions factors remain as final emission factor estimates. Many default emission factors for fuel combustion take into abatement measures, by incorporating a control percentage:

Default $EF_{i,j,k,n}$ = Base $EF_{i,j,k,n}$ x (1 - Control $Percentage_{i,j,k,n}$)

where:

- EF = Default Emissions Factor,
- Base EF = default Emissions factor before control percentage adjustment,
- Control Percent = Estimate of the percent reduction in final emissions due to control/mitigation efforts. Value between 0 and 1,
- i = country,
- j = sector,
- k = fuel,
- n = year.

Sometimes default emission factors are calculated directly from data sources with energy use and emissions estimates (such as GAINS). In those cases, the calculated implied emission factors included abatement measures. In those cases, they are processed like similar to base emission factors, where the corresponding control percentage is 0.

5.1. SO_2

5.1.1. Base SO_2 Emission Factors

Base SO_2 Emission Factors are calculated from sulfur content and ash retention of fuels using the following equation:

$EF_{base\_SO2} = S_{content}$ * 2 * (1 - Ash Retention) where:

EF_{base_SO2} = SO_2 Base emission factor,

$S_{content}$ = sulfur content of fuel as fraction between 0 and 1,

Ash Retention = sulfur ash retention as fraction between 0 and 1.

Sulfur Content

Diesel

Diesel sulfur content for road transport is set using a compilation of sulfur standards from multiple sources, including UNEP reports, Kholod et al. 2015, and Gschwandtner et al. 1985. For a complete list of sources, refer to *Diesel_transport_S_trend.xlsx*.

This data is used as default SO_2 emission factors for road transportation diesel oil. In interpolating and extending data estimates, we assume a starting value of 8000 ppm in 1970, extend the most recent standard through 2015, and use regional average for countries with no data. As with all other emission factors, these default estimates are scaled to match country-level inventory estimates were available.

Other Fuels

Sulfur content for fuels other than diesel are derived from output from the GAINS global model (IIASA 2014a).

GAINS sulfur content values are for 2005 only and are assumed constant over time from 1960 - 2014 except for heavy oil, for which GAINS sulfur content values are assumed to converge to Mylona (1996) defaults, with some exceptions as informed by comparison with country inventory estimates.

Exceptions from Other Data Sources

Jet Fuel: The sulfur content for light oil and heavy oil for all countries is set to 0.00059 for domestic aviation (1A3aii_Domestic-aviation) and 0.000528 for international aviation (1A3ai_International-aviation). These values were selected by an iterative processes while scaling to EDGAR.

Shipping: The sulfur content for international shipping (1A3di_International-shipping) and domestic navigation (1A3dii_Domestic-navigation) for diesel oil and heavy oil are taken from the the IMO (IMO 2014).

Heavy Oil - Asia: sulfur content for heavy oil in select Asian countries (khm, chn, hkg, idn, mys, mng, mmr, vnm) were taken from RAINS Asia default sulfur content for 1990 (Foell 1995). sulfur content for sgp, phl, thi where matched to REAS inventories.

Heavy Oil - Europe: In the following countries, sulfur contents for heavy oil in many combustion sectors were set to converge to Mylona (1996) values as defaults (many .033 by 1960): aut, bel, bgr, cyp, cze, deu, dnk, esp, est, fin, fra, gbr, grc, hrv, hun, irl, ita, ltu, lux, lva, mit, nld, pol, prt, rou, svk, svn.

Heavy Oil - North America: Sulfur content for heavy oil in US and Canada (usa, can) in all sectors for the years 1960, 1970, 1980, 1990, and 2005 were taken from Environment Canada's report on Sulfur in Liquids(Environment Canada 2016) and inferred from EPA's trends in sulfur emissions (US EPA 2015).

Heavy Oil - Taiwan: Sulfur content for heavy oil for all sectors in Taiwan is from RAINS Asia (Foell et al. 1995) through 1990 and matched to Taiwan national inventory after that through 2015 (TEPA 2016).

China - Coal Electricity: sulfur content for hard coal for China, public electricity (1A1a_Electricity-public) was set to 0.0101 in 1990 and .0095 according to Liu et al. (2015).

South Africa - Coal electricity: sulfur content for hard coal and brown coal for public electricity in South Africa were taken from Pretorius et al. (2015).

Eastern Europe - Coal: GAINS Europe sulfur contents reflect relatively recent conditions. Analysis of initial CEDS results indicated that use of current coal sulfur contents underestimated emissions in several; Eastern European countries. Default coal sulfur contents were therefore increased from 2000 to 1990 and again from 1990 to 1980 in cze, svk, and pol. The resulting remissions were a better match to EMEP gap-filled “expert” emissions estimates.

FSU coal: sulfur content in all sectors in the following countries were set according to Ryaboshapko et al. (1996): arm, aze, blr, est, geo, kaz, kgz, tu, lva, mda, rus, tjk, tkm, ukr, uzb

Great Britain - coal: Sulfur content for hard coal in the industry, RCO, and public electricity sectors from 1970 - 2013 was set according to the UK National Atmospheric Emissions Inventory (NAEI) (UK DEFRA 2013).

RAINS Asia - coal: Sulfur content in hard coal and brown coal in the following countries for all sectors were taken from RAINS Asia (Foell et al. 1995): bgd, btn, khm, hkg, ind, idn, jpn, prk, mys, npl, sgp, twn, tha, vnm, ind, mng, mmr, pak, phl, tha

South Korea: Sulfur content for hard coal and heavy oil for all sectors in South Korea was taken from the South Korean Inventory for 1970 - 2010, and from RAINS ASIA (Foel et al. 1995) for 1990.

Turkey: Sulfur content for brown coal in Turkey from 1970 - 2002 set to 1.5%, which results in electric power sector emissions in 2003/2004 similar to that of Say(2005).

USA: Sulfur content in the US for hard coal in most sectors from 1950 - 1980 is from Gschwandtner and Gschwandtner (1985) and inferred from EPA trends through 2002 (EPA 2002).

Ash Retention

GAINS Europe

Sulfur content for fuels other than diesel are from output from the GAINS model (IIASA 2014b). GAINS ash content values are for 2005 only and are assumed constant overtime from 1960 - 2014.

Exceptions from Other Data Source

China - Coal Electricity: sulfur ash retention for hard coal for China, public electricity (1A1a_Electricity-public) was set to 0.15 according to Liu et al. (2015).

FSU - coal: sulfur ash retention in all sectors in the following countries were set according to Ryaboshapko et al. (1996): arm, aze, blr, est, geo, kaz, kgz, tu, lva, mda, rus, tjk, tkm, ukr, uzb

South Africa - Coal Electricity: sulfur ash retention for hard coal and brown coal for public electricity in South Africa was set to 0.06 according to Pretorius et al. (2015).

5.1.2. SO_2 Control Percentage

Pre 2005 SO_2 Control Percent

SO_2 control percentages for Europe are calculated using output from the GAINS model.

Apparent SO_2 EFs for 2005 are calculated using GAINS energy and emissions data as

$EF_{apparent\_SO2}$ = Emissions / Energy

for each iso-sector-fuel-combination. The control percent is calculated as

Control Percent = $EF_{apparent\_SO2}$ / EF_{base_SO2}

where EF_{base_SO2} is calculated as shown above. SO_2 control percentages are assumed to equal 0 in 1990 and are linearly interpolated between 1990 and 2005.

Recent SO_2 Control Percent

The recent control percent is defined as control percent between the last inventory year and the last year in GAINS EMF30 data for a specific country so for that country the control percent after last inventory year can follow trend shown in GAINS EMF30 data. For each country in GAINS EMF30 data, a recent ratio is calculated as

recent_ratio = $GAINS\_EMF30\_EF_{year}$ / $GAINS\_EMF30\_EF_{last\_inventory\_year}$

Then the recent_ratio is used to calculate recent control percent as

recent_ratio * (1 - $control\%_{last\_inventory\_year}$) = 1 - $control\%_{year}$

SO_2 Control Percent from Other Data Source

China - Coal Electricity: SO_2 Control percentages for China coal-fired public electricity are from from Liu et al.(2015). Control percent is set as 0 in 2000, .1 in 2005, and .78

Japan - Coal electricity: SO_2 Control percentages for Japan public electricity from hard coal are set to 0 in 1970 and .95 in 1980.

Philippines - Coal electricity: SO_2 Control percentages for Philippines public electricity from hard coal are set to 0 in 2000 and .7 in 2008 according to the REAS inventory (Kurokawa 2013).

South Korea - Coal electricity: SO_2 Control percentages for Philippines public electricity from hard coal are set to 0 in 2000 and .7 in 2008 to better match REAS inventory (Kurokawa 2013).

Taiwan - Coal electricity: SO_2 Control percentages for Taiwan coal public electricity and heat production(1A1a_Electricity-public and 1A1a_Heat-production) are set to 0 in 1994, .8 in 2000, and .9 in 2005, and .95 in 2010 are adjusted to better match emission from Taiwan's National Inventory (TEPA 2016).

Thailand - Coal electricity: SO_2 Control percentages for Thailand coal public electricity and heat production(1A1a_Electricity-public and 1A1a_Heat-production) are set to 0 in 1980, .85 in 2000, and .95 in 2001 are adjusted to better match emission from Simachaya (2015).

5.2. BC and OC

5.2.1. Base BC and OC Emission Factors

Base Emission Factors for BC and OC are calculated from the SPEW Database (Bond et al. 2007) as reported emissions divided by fuel consumption for each country, fuel, sector, and year. Emission factors are estimated from SPEW. Emission factors are calculated as a weighted average for CEDS fuels and sectors, according to SPEW data.

- FSU emissions factors for residential coal, oil, and gas are replaced with EF estimates for FSU industrial coal, oil, and gas respectively. This was done since the residential sector in the FSU is dominated by centralized heating technologies that are more typical of industrial boilers than small-scale combustion installations.
- For all regions, residential biomass emissions factors for 2001 and beyond are set equal to the SPEW 2000 values since the SPEW database used did not contain biomass emissions past 2000.

Unless otherwise mentioned, emission factors are linearly interpolated between data points and constantly extended forward and backward over missing years. Complete time series of missing emission factors for country-fuel-sector combinations are replaced using the following estimates in order:

- Region-sector-fuel average
- Region-fuel average
- Global-sector-fuel average
- Global-fuel average

5.2.2. BC and OC Control Percent

The recent control concept for BC and OC is similar to the recent control concept for SO_2, except the last inventory year for SO_2 are different for different countries, while for BC and OC last inventory year is unified as year 2010. For each country, the recent control percent is calculated using GAINS EMF30 data so the trend for control percent follows the trend in GAINS EMF30 data.

5.3. NH_3

NH_3 emission factors for all countries are calculated using the US National Emissions Inventory (NEI) (US EPA 2013), which provides default EFs by fuel and summary sector for the US. While we use US values for base EFs for all countries, many NH_3 final emissions estimates are scaled to country inventories. Additionally, NH_3 emissions from combustion sectors make up only 8% of global NH_3 emissions (in 2010), which are dominated by agricultural process emissions.

5.3.1. Other: NO_X, NMVOC, CO

Emission Factors for other species (NO_X, NMVOC, CO) are from GAINS EMF-30. Where available emission factors are fuel, sector and country specific. When unavailable, emission factors are estimated in the following order:

- same fuel, same sector, region average
- same fuel, same country, aggregate sector average
- same fuel, aggregate sector, OECD (or non-OECD) average

5.3.2. Default EFs from data sources

Some default emission factors are taken directly from data sources, rather than calculated from base EF and control percentages.

5.3.3. NO_X, CO, and NMVOC

Aircraft

EF's for all countries for diesel and light oil (1970 - 2010, 1A3aii_Domestic-aviation and 1A3ai_International-aviation) are calibrated to average EDGAR inventory EF values.

Ship and Rail

EF's for all countries for light, diesel, and heavy oil (1970 - 2010, 1A3dii_Domestic-navigation and 1A3di_International-shipping) are taken from the International Maritime Organization (IMO) Third IMO GHG Study 2014 (Smith et al. 2014). EF's for all countries for hard_coal (1970 - 2010, 1A3c_Rail) unless otherwise noted are assumed to be early industrial coal boiler values (0.0046 kg NO_X/kg coal).

5.3.4. BC, OC

Aircraft

EF's for all countries for diesel and light oil (1970 - 2010, 1A3aii_Domestic-aviation and 1A3ai_International-aviation) are calibrated to average EDGAR inventory EF values.

Ship and Rail

EF's for all countries for light, diesel, and heavy oil (1970 - 2010, 1A3dii_Domestic-navigation and 1A3di_International-shipping) are from Eyring et al. (2010) EF, scaled down by ratio of total PM from Eyring et al. (2010) to Third IMO GHG Study (Smith et al. 2014)in 2007. EF's for all countries for hard_coal (1970 - 2010, 1A3c_Rail) unless otherwise noted are assumed to be average values from SPEW database (0.001 kg BC/kg coal).

5.4. CO_2

The approach for estimating CO_2 emissions generally follows methodologies and assumptions used in CDIAC, with modifications to adapt this approach to the sectoral emissions calculations in CEDS, as described below.

CO_2 Emission Factors for brown coal, hard coal, and natural gas are assumed to be proportional to fuel energy content, as also assumed in other inventories (Olivier et al. 2015, IEA 2016). We use CDIAC emission coefficients as follows:

```
Emission_Factor = Emission_Coefficient (kg CO~2~/kJ fuel) * Energy_Content (kJ fuel/kt
fuel) * Fraction_Oxidized
```

Where the CDIAC Emission_Coefficient is (Boden et al. 1995):

- Natural Gas: 5.01968E-11 kt CO_2/kJ fuel
- Coal: 9.05E-11 kt CO_2/kJ fuel (already accounting for fraction oxidized)

The Energy_Content for natural gas is taken to be 44.2 TJ/kt. For brown and hard coal Energy_Content is from IEA Energy Statistics. The energy content is assumed constant over time before 1960 (OECD countries) and 1970 (non-OECD countries).

CO_2 Emission Factors for liquid fuels (CEDS fuels are: heavy, light, and medium oils) and coal coke are from EIA emission coefficients:

```
Emission_Factor = Emission_Coefficient (kg CO~2~/gallon fuel) / Fuel_Density (kg
fuel/gallon fuel) * Fraction_Oxidized
```

EIA emission coefficients can be found at: https://www.eia.gov/environment/emissions/co2_vol_mass.cfm. Due to the different emissions coefficient of jet fuel, we use a different CO_2 Emission_Factor for medium oil used in aviation vs other sectors.

Note that our use of fuel-specific emission factors for liquid fuels is a departure from CDIAC's use of a generic liquid fuel emissions factor because CEDS distinguishes between specific liquid fuel types by sector. This should result in a more realistic sectoral distribution of emissions for the CEDS estimate.

All CO_2 emissions factors were multiplied by a fuel-specific effective fraction oxidized from CDIAC (Boden et al. 1995):

- Solid fuels: 0.982
- Liquid fuels: 0.985
- Natural gas: 0.98
- Bunker fuels: 1

Note we have used CDIAC liquid fuel oxidation fractions Given that CDIAC oxidation fractions for "when non-energy liquid products are specifically subtracted", which is the case in CEDS. We use a different oxidation fraction for China coal as noted below.

The resulting global default emission factors for liquid fuels and coal coke (including oxidation fraction) are:

- Heavy oil: 4.321070002 kt CO_2/kt fuel
- Diesel oil: 3.185367087 kt CO_2/kt fuel
- Diesel oil (aviation sectors): 3.046194958 kt CO_2/kt fuel
- Light oil: 3.08449713 kt CO_2/kt fuel
- Coal coke: 3.063689023 kt CO_2/kt fuel

The oxidation fraction represents carbon that is not oxidized either directly to CO_2 or to other species that will eventually oxidize over annual to decadal timescales (e.g. CO, VOCs, CH_4). We note that there are differences in suggested methodology in terms of the use of a default oxidation fraction when estimating CO_2 emissions. While the 1996 IPCC emission factor guidelines recommended use of an oxidation fraction (ranging from 99.5% for natural gas to 98% for coal), the 2006 guidelines recommend assuming 100% "unless better information is available". To be consistent with CDIAC, and also to prevent overestimating emissions, we use a constant default oxidation fraction for all years as described above.

Note that CEDS follows established convention for estimating CO_2 emissions whereby these emissions represent all carbon that is emitted from each sector in oxidized form. There is, therefore, some double counting within the CEDS inventory between carbon emitted as CO_2 and carbon emitted as CO or VOCs. This should be kept in mind by users.

We note that it is not clear if the various definitions of oxidation fraction in the literature are consistent. For example, it is not clear how carbonaceous aerosols emitted from combustion should be considered. In the CEDS inventory, however, emitted BC+OC comprise 0.2% or less of the carbon content of coal in early years, so BC+OC emissions doe not appear to comprise a signifiant issue for coal carbon accounting.

A recent review (Bartoňová 2015) notes the fraction of unburnt carbon in coal ash depends on both combustion technology and coal characteristics. For well-run coal-fired power plants, for example the oxidation fraction tends to be high - with very little unburnt carbon, while for less-efficient stoker-style coal boilers, up to around half the ash could be composed of carbon (Bartoňová 2015). It is, therefore, possible that CO_2 emissions, as estimated here, could be slightly overestimated for earlier times when less efficient coal combustion technologies were in use.

Given our use of a default oxidation fraction not equal to 1, we note the work of Liu et al. (2015) for China. Liu et al. argue that a lower oxidation fraction is appropriate for China given the relatively poor quality and high ash content of Chinese coal. Liu et al. use a "source-weighted" oxidation fraction of 92%. However, as noted above, the oxidation fraction depends also on technology. This is also seen in oxidation fractions from China's National Development and Reform Commission (NDRC) Tier 1 values (as complied by Liu et al. 2015), where an oxidation fraction of 0.98 is reported for raw coal thermal power plants, 0.94 for industrial combustion, and even lower, 0.85, for service and other sectors. The NDRC tier 2 figures, also from Liu et al., differ: 0.94 for raw coal in all sectors. Note that Liu et al. use a "production-weighted" oxidation fraction of 0.92, which accounts for their lower emissions relative to other inventories (see discussion in Olivier et al. 2015). Given the large amount of coal used for thermal power production in China, where the oxidation fraction is expected to be higher than this - at least in modern plants, this might be an overestimate of the amount of unburned carbon for China.

We note that a the high ash content of coal in China is also thought to impact other emission species, for example via a higher sulfur retention in ash in the GAINS model (Wang et al. 2014) and also in the MEIC inventory used in CEDS (Li et al. 2017). For consistency, we also account for this in the calculation of CO_2 emissions from China. If we assume an oxidation rate of 0.98 for thermal power plants and 0.94 for other sectors (consistent with NDRC Tier 1 values), then the average value for China coal over recent years is 0.96. We, therefore, use 0.96 for the oxidation rate for brown and hard coal in China. This is larger than the Liu et al. value, but smaller than the CDIAC default value.

The fraction of liquid fuels produced from biofuels for each country are inferred from IEA energy statistics. After emission factors are calculated from emission coefficients and oxidation fraction, EF are weighted according to fraction of liquid biofuels for each country, where EFs for biofuels are equal to zero.

CO_2 emissions for most OECD countries are scaled to match UNFCCC inventory submissions over 1990-2012.

6. Default Process (Non-Combustion) Emissions and Emission Factors

EDGAR is used default process emissions for most non-combustion sectors, with some exceptions as noted below. Where these default emissions for a specific country and sector were substantially lower than emissions in country-level inventories, default process emissions were estimated with both EDGAR trends and country inventory values (explained below)

6.1. Edgar

Non combustion emissions for most sectors were taken directly from EDGAR (EC-JRC/PBL 2016). A detailed mapping of CEDS working sector to EDGAR process is available in the Appendix A2.

6.2. Fugitive Petroleum and Gas

Emissions from the 1B2_Fugitive-petr-and-gas sector include emissions from oil and gas extraction along with emissions from refineries and other production processes.

A key source for this sector is flaring emissions, largely from oil production. The flaring country level emissions used in CEDS are extracted from ECLIPSE V5a Flaring emissions Baseline CLE gridmap for year 1990, 2000, and 2010. The ECLIPSE flaring gridmaps are available from http://www.iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv5a.html. Then the year 1990, 2000, 2010 ECLIPSE flaring emissions are extended to annual data from 1965 to 2014 using oil production time series from BP and IEA.

The ECLIPSE flaring emissions are often much larger than emissions from "Fugitive emissions from oil and gas" in EDGAR, which we interpret as a general underestimation of these emissions in EDGAR. Because there are additional sources in this sector we take a conservative approach in combining these two datasets. Default 1B2_Fugitive-petr-and-gas emissions used in CEDS are generated as a combination of EDGAR JRC PEGASOS data (a.k.a. EDGAR 4.3) for Fugitive emissions from oil and gas and extended ECLIPSE flaring emissions for year 1965 to 2014. The maximum value of the EDGAR JRC PEGASOS Fugitive emissions from oil and gas emissions and extended ECLIPSE flaring emissions for a specific country/region – year combination is found, and then the max value are taken as default CEDS Fugitive Petroleum and Gas emissions for that country/region and year.

As with all default emissions, these values are then scaled to match country-level inventory data where this is available.

6.3. Waste Combustion

Default waste combustion EFs by country for 2010 are available for the following emissions species: SO_2, NO_x, CO, NMVOC, BC, OC, NH_3, CH_4, CO_2 (Wiedinmyer et al. 2014)

For CO_2 only, the default waste incineration emissions factors are adjusted by multiplying with the fraction of fossil fuel times urban population shares. The default fossil fractions for waste emissions are assumed to be:

- for high-income countries: 0% in 1940; 1.5% in 1965; 7% in 1985; 10% in 1990, and 20% in 2000 and forward.
- for low- and middle-income countries: 0% in 1980, 15% in 2000 and forward

linearly interpolated and extrapolated as appropriate.

6.4. Wastewater NH_3

Default Wastewater sector emissions are taken to include emissions from untreated waste. NH_3 emissions from untreated waste are taken to be far higher than that from treatment facilities, therefore default NH_3 emissions are taken to be:

```
Emissions = Emissions Per-Capita * Population * (1 - Wastewater Treatment Ratio)
```

where Wastewater Treatment Ratio is ratio of population with wastewater treatment.

Default wastewater NH_3 emissions for persons living in areas without wastewater treatment were assumed to be 1.6 kg/person/year globally in recent years - this value is that used in REAS, which was taken from the EMEP/CORINAIR Guidebook. This value was assumed to decline slightly back to 1850 due to lower nitrogen intake (following Davidson 2009).

Data for wastewater treatment was taken from OECD and UN wastewater treatment indicators, and REAS for Asian countries, in that order of priority. Data for wastewater treatment percentages are incomplete, so proxy countries/trends are used where direct data was not available. Wastewater treatment percentage is assumed to increase over time, and generally decrease to 0 in 1900 for all countries (0 in 1970 for countries with no 1970 original data).

In addition, the following assumptions for wastewater treatment percentage were made:

- Several African, small Asian countries and islands where no data exists: 0% wastewater treatment for all years

- India: 0% wastewater treatment in 1978 (Kaur 2012)
- Russia and Ukraine: 70% wastewater treatment in 2005 (UN Sanitation Country Profile)
- Georgia: 30% wastewater treatment in 2005
- China: follows relative trend in Figure 1 of Zhou et al. (2011), and 0% wastewater treatment in 1980.

6.5. SO_2

6.5.1. Pulp and Paper SO_2

SO_2 emissions from pulp and paper production are download from the FAOSTAT Database of the Food and Agricultural Organization (FAO) of the United Nations, using the R package "FAOSTAT".

6.5.2. SO_2 - Additional Petroleum Processing

Mclinden et al. (2016) have compared satellite-derived SO_2 emission estimates, compared to gridded emission inventories, to identify a number of missing sources of SO_2, particularly from the oil and gas sector. There are two potential reasons for such missing sources. One is out of date gridding proxies. In this case the emission might be included in an inventory, but not accurately mapped to the spatial grid. In this case, while a revision to the spatial data used to map emissions to a spatial grid might be needed, the total emissions in the inventory would not require correction. However, it is also possible that the emissions are actually under-represented in the country-level inventory. (A combination of these might also occur.) We take a conservative approach to determine cases where emissions appear to be underestimated in our CEDS default data and use the Mclinden et al. (2016) results to improve our inventory estimate.

We compared the total magnitude of the emissions from missing sources in Mclinden et al. (2016) to our inventory data by country. We found several cases where the sum of the Mclinden et al. missing oil and gas emissions in a country were greater than the corresponding emissions in the initial version of the CEDS emission data (which were generally, for these sectors and countries, originally from EDGAR). We assumed in these cases that emissions were underestimated. In order to be conservative and avoid double counting, we subtracted the CEDS default values from the Mclinden et al. "oil and gas" missing emissions for each country, and added this difference to the CEDS estimates. This essentially sets the CEDS estimates for the sum of the two sectors 1A1bc_Other-transformation and 1B2_Fugitive-petr-and-gas to the Mclinden et al. missing emissions. Since only missing emissions were identified by sector in Mclinden et al., this would underestimate actual emissions if there were additional sources for this sector in both the satellite and gridded emissions data examined by Mclinden et al.

This procedure resulted in a net global addition in 2010 of 3,900 kt of SO_2. The largest addition was to Iran, but emissions were also added in Aruba, Kazakhstan, Mexico, Qatar, Russia, Saudi Arabia, United Arab Emirates, and Uzbekistan.

The Mclinden et al. estimates span 2005 through 2014. These data were extrapolated back to 1965 using oil production data from the BP energy statistics, and before 1965 using CDIAC liquid fuel CO_2 emissions. This extention resulted in significant SO_2 emissions in Iran (peaking at 1,800 kt/yr) during the 1970s as oil production peaked in that country.

The historical extrapolation could be improved if the SO_2 emission sources could be classified into oil production facilities vs oil refining facilities, which could separately be extrapolated over time using crude oil production and refinery output, respectively.

By using the Mclinden et al. data we were able to, relatively quickly, fill in some large gaps, and improve the inventory. More detailed comparison and analysis could likely add further improvements to the emission data.

6.5.3. SO_2 - Metal Smelting

SO_2 metal smelting emissions for all countries are from updated values from Smith et al. (2011).

6.6. CO_2 - CDIAC Cement Production

CO_2 non-combustion Emission Factors for cement production are derived from CDIAC emissions data. Since CDIAC data are only available until 2011, we extend cement emissions to recent years using USGS cement production data, such that cement emission factors for the extended years (2012-2015) equal 2009-2011 average emission factors.

6.7. Miscellaneous Process Emissions

BC, OC - China - Coke Production: China coke production (1A1bc_Other_tranformation) for 1990 - 2014 were estimated with 1990 and 1995 estimates from SPEW (Bond et al. 2007), extended and trended with values from Huo et al. (2012).

NMVOC - Tanker Crude Oil Loading: Emissions from the loading of crude oil on to Tankers IMO GHG study (2014) scaled by crude oil transport from UNCTAD until 1970, then by CDIAC CO_2 from petroleum. These estimates are mapped to the 'global' country (as are many shipping emissions) rather than attributed to individual countries.

6.8. Emissions directly from Inventories

As described in the main text (Section 2.3.2), throughout the scaling process, non combustion emission for select countries and sectors were discovered to be orders of magnitude different from reported inventory data. In these cases, non combustion emissions estimates are taken from both EDGAR and the country inventories. Inventory values are gap filled and extended back to 1970 following EDGAR trends (most country inventories do not extend back to 1970, the starting point of the EDGAR data).

Table 2. Non-Combustion Emissions from Inventories

Emission Species	Inventory	Sector	Country
SO_2	UNFCCC	1B2_Fugitive-petr-and-gas	grc, nzl
SO_2	REAS	1A1bc_Other-transformation	tha, mys

Emission Species	Inventory	Sector	Country
SO_2	REAS	2B_Chemical-industry	bgd
SO_2	EMEP	1B2_Fugitive-petr-and-gas	rou, aut, bel, che, deu, dnk, esp, fin, fra, gbr, hun, ita, ltu, nor, pol, prt, swe
SO_2	Argentina National Inventory	1B2_Fugitive-petr-and-gas	arg
NO_X	UNFCCC	1B2_Fugitive-petr-and-gas	grc
NO_X	REAS	2B_Chemical-industry	twn
NO_X	REAS	3D_Soil-emissions	mng, btn
NMVOC	UNFCCC	2D_Chemical-products-manufacture-processing	blr
NMVOC	REAS	1A1bc_Other-transformation	idn, phl, lka, mng
NMVOC	REAS	2D_Degreasing-Cleaning	sgp, brn
NMVOC	REAS	2D_Paint-application	ind, kaz, mdv, mmr, pak, tha, tkm, vnm
NMVOC	REAS	2D_Chemical-products-manufacture-processing	ind, kaz, kgz ,mmr, mng ,prk ,tkm, twn, uzb, vnm, jpn
NMVOC	EMEP	1A1a_Electricity-public	geo
NMVOC	EMEP	1B2_Fugitive-petr-and-gas	swe, che, hrv, esp, ltu, lva
NMVOC	EMEP	2D_Degreasing-Cleaning	bgr
NMVOC	EMEP	5C_Waste-combustion	esp, che
NMVOC	MEIC	2D_Chemical-products-manufacture-processing	chn
NMVOC	MEIC	5C_Waste-combustion	chn

Emission Species	Inventory	Sector	Country
NMVOC	Canada Trends	2D_Chemical-products-manufacture-processing	can
NMVOC	Canada Trends	5C_Waste-combustion	can
NMVOC	Canada Trends	2D_Paint-application	can
NMVOC	MEIC	5C_Waste-combustion	chn
NH_3	REAS	3B_Manure-management	chn, ind, pak, jpn, idn, bgd, vnm, mng, tha, mmr, phl, npl, afg, kor, twn, mys, khm, lao, prk, btn, lka, uzb, kaz, brn, tjk, kgz, tkm, sgp, mdv
NH_3	REAS	3D_Soil-emissions	chn, ind, pak, idn, vnm, bgd, tha, phl, jpn, mmr, npl, mys, kor, twn, lka, prk, khm, lao, mng, afg, btn, uzb, kaz, kgz, brn, tjk, tkm, sgp, mdv
NH_3	REAS	5D_Wastewater-handling	chn, ind, idn, bgd, pak, phl, vnm, tha, mmr, jpn, uzb, npl, afg, mys, prk, kor, ka, kaz, khm, twn, tjk, lao, kgz, tkm, mng, sgp, btn, mdv, brn
NH_3	EMEP	5D_Wastewater-handling	prt, cze, est, fin, mlt, svn, cyp, che, bgr, swe, ukr, hun, lva, tur, bel, hrv, mda, pol, blr, gbr, srb
CO	REAS	1A1bc_Other-transformation	idn, sgp, twn, chn
CO	UNFCCC	2B_Chemical-industry	blr
CO	EPA Trends	2B_Chemical-industry	usa

7. Scaling to Inventories

The scaling method is discussed in Section 2.4 of the main text. The following table details the scaling process for NO_X emissions in Sweden in 1995, using the EMEP NFR 14 inventory.

The scaling process is sequential and countries are often scaled to multiple inventories (e.g. EDGAR and a national inventory). In these cases, we scale "default emissions estimates" to EDGAR, then scale "EDGAR scaled estimates" to the national inventory. During the scaling process, CEDS default emissions are aggregated to scaling sectors, matched to the inventory values, then disaggregated back to CEDS sectors based on default emission values. Because different inventories have different mappings to aggregate scaling sectors, the makeup of default emissions in CEDS sectors within an aggregate scaling sector is not always retained from default emissions through to final scaled emissions. For example, as shown in the table below, 1A4a_Commercial-institutional makes up 50% of default emissions in the scaling sector 'Other Stationary Combustion', but only 16% of final scaled emissions in 'Other Stationary Combustion'. This is because the four sectors that make up 'Other Stationary Combustion' were not all scaled together by previous inventories. When scaling to EDGAR 1A4a_Commercial-institutional,1A4b_Residential, and 1A4c_Agriculture-forestry-fishing are scaled together. When scaling to EMEP NFR 09 1A4a_Commercial-institutional,1A4b_Residential, and 1A5_Other-unspecified are scaled together. This occurs because inventories do not report sectors, especially "other" sectors consistently. This is a potential source of uncertainty, especially in more recent years, when sectors reporting "other" emissions become larger percents of totals due to mitigation efforts.

Table 3. Scaling Emissions Example - Sweden NOx (1995)

CEDS Sector	Default Emissions [kt]	Scaling Sector	Inventory Emissions [kt]	Final Scaled Emissions [kt]
1A1a_Electricity-public	0.319	Public Power	12.35	.157
1A1a_Heat-production	24.7			12.2
1B1_Fugitive-solid-fuels	0	Fugitive	.129	0
1B2_Fugitive-petr-and-gas	6.62E-6			.129
1B2d_Fugitive-other-energy	0			0
1A4a_Commercial-institutional	24.45	Other Stationary Combustion	9.17	1.46
1A4b_Residential	5.36			.319
1A4c_Agriculture-forestry-fishing	18.9			7.38
1A5_Other-unspecified	.06			0.015

7.1. EDGAR 4.3

Unless otherwise noted, the following countries are scaled to EDGAR 4.3 from 1992 - 2009:

can, spm, usa, mex, abw, aia, ant, atg, bhs, blz, bmu, brb, cri, cub, cym, dma, dom, glp, grd, gtm, hnd, hti, jam, knalca, msr, mtq, nic, pan, pri, slv, tca, tto, vct, vgb, bra, arg, bol, chl, col, ecu, flk, guf, guy, per, pry, sur, ury, ven, dza, egy, esh, lby, mar, tun, ben, bfa, caf, civ, cmr, cod, cog, cpv, gab, gha, gin, gmb, gnb, gnq, lbr, mli, mrt, ner, nga, sen, shn, sle, stp, tcd, tgo, bdi, com, dji, eri, eth, ken, mdg, mus, reu, rwa, sdn, som, syc, uga, ago, bwa, lso, moz, mwi, nam, swz, tza, zaf, zmb, zwe, aut, bel, che, deu, dnk, esp, fin, fra, fro, gbr, gib, grc, grl, irl, isl, ita, lux, nld, nor, prt, swe, alb, bgr, bih, cyp, cze, est, hrv, hun, ltu, lva, mkd, pol, rou, scg, svk, svn, blr, mda, ukr, kaz, kgz, tjk, tkm, uzb, arm, aze, geo, rus, are, irn, irq, isr, jor, kwt, lbn, omn, qat, sau, syr, yem, afg, bgd, btn, ind, lka, mdv, npl, pak, kor, prk, chn, hkg, mac, mng, twn, brn, khm, lao, mmr, mys, phl, sgp, tha, tls, vnm, idn, png, jpn, aus, cok, fji, kir, ncl, nzl, plw, pyf, slb, ton, vut, wsm, sea, air

Rail emission for all countries are only scaled from 2000 - 2009. rou is not scaled in the years 1992 or 2000. mkd is not scaled in 1992. svk is scaled from 2000 - 2009

7.2. EMEP NFR09

Unless otherwise noted, the following countries are scaled to EMEP (NFR09 sector definitions) from 1980-2012:

aut, bel, bgr, che, cyp, cze, deu, dnk, esp, est, fin, fra, gbr, geo, hrv, hun, irl, isl, ita, ltu, lux, lva, mkd, nld, nor, pol, prt, rou, svk, svn, swe

- mkd is scaled from 2000-2010
- fin is scaled from 1982 - 2012
- lux road and rail emissions are scaled from 1990 - 2012

For SO_2 only: - mkd is scaled from 1990 - 2012 - fin is scaled from 1982 - 2012 - lux road and rail emissions are scaled from 1990 - 2012 - svn is scaled from 1990 - 2012

7.3. EMEP NFR14

Unless otherwise noted, the following countries are scaled to EMEP (NFR14 sector definitions) from 1980-2013:

aut, bel, bgr, che, cyp, cze, deu, dnk, esp, est, fin, fra, gbr, geo, hrv, hun, irl, isl, ita, ltu, lux, lva, mkd, nld, nor, pol, prt, rou, svk, svn, swe

- mkd is scaled from 2000-2010
- fin is scaled from 1982 - 2013
- lux road emissions are scaled from 1990 - 2013

For SO_2 only: - mkd is scaled from 1990 - 2013 - fin is scaled from 1982 - 2013 - lux road and rail emissions are scaled from 1990 - 2012 - svn is scaled from 1990 - 2013

7.4. UNFCCC

Unless otherwise noted, the following countries are scaled to UNFCCC from 1990 - 2012: blr, grc, nzl

- grc is not scaled in 2006 or 2010

7.5. Others

Scaling to following inventories have no exception and special assumptions:

REAS

The following countries are scaled to REAS (Kurokawa et al. 2013a) from 2000-2008:

afg, bgd, brn, btn, idn, ind, kaz, kgz, khm, lao, lka, mdv, mmr, mng, mys, npl, pak, phl, prk, sgp, tha, tjk, tkm, twn, uzb, vnm

CAN

Canada estimates for SO_2, NO_X, NMVOC, CO are scaled first to Canada’s national emissions trends (Environment Canada 2010) from 1985-2011, and then to newer estimates from the Canada National Pollutant Release Inventory over 1990 - 2013.

USA

USA estimates for SO_2, NO_X, NMVOC, CO, NH_3 are scaled to US EPA trends (US EPA 2013) from 1970, 1975, 1980, 1985, and 1990-2014. NH_3 emissions are scaled for 1990 - 2014.

China

Estimates for all emission species in China are scaled to MEIC (Li et al. 2017) for 2008, 2010, and 2012.

Argentina

SO_2, NO_X, CO, and NMVOC estimates for Argentina are scaled to the Argentina UNFCCC submission for 1990-1999, 2001-2009, and 2011.

Japan

Japan estimates for SO_2, NO_X, NMVOC, CO, NH_3 are scaled to a preliminary updated version of REAS (Kurokawa et al. 2013b) for 1960 - 2010.

South Korea

SO_2, NO_X, CO, and NMVOC estimates for South Korea are scaled from 1999 - 2012 (South Korea National Institute of Environmental Research, n.d.).

Taiwan

SO_2, NO_X, CO, and NMVOC estimates for Taiwan are scaled to the Taiwan Emissions Data System (TEPA 2016) for 2003, 2006, and 2010.

Australia

SO_2, NO_X, CO, and NMVOC estimates for Australia are scaled to the Australia National Inventory (Australian Department of the Environment 2016) for 2000, 2006, and 2012.

8. Historical Emissions Extension

8.1. Activity Data

8.1.1. Fossil Fuel Extension

IEA Energy Statistics, which are the foundation for energy estimates in this data set, end at 1960 for OECD countries, and 1971 for most Non OECD countries. Fossil fuels are extended using a combination of SPEW, CDIAC, and IEA statistics.

First total fuel use for three aggregate fossil fuel types, coal, oil, and gas, are estimated over 1750 - 1960/1971 for each country using historical national CO_2 estimates from 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 CO_2 time series, resulting in an annual time series.

For coal, petroleum, and natural gas, 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 1971 or 1960 to SPEW sectoral splits by 1850. It was not always possible to rely on bond sectoral splits. When SPEW data was estimated zero fuel use in a given sector assumptions were made about sectoral fuel use splits according to the following table. In cases where IEA extended fuel use estimated non zero fuel use, but SPEW estimated zero fuel use, these assumptions were necessary to avoid "dropping" energy use from disaggregate estimates.

Table 4. Sector Split of Fuel Use in Early Years

Fuel	Aggregate Sector	Percent
Agriculture-Forestry-Fishing	natural gas	0
Industry	natural gas	0.5
Power	natural gas	0
RCO	natural gas	0.5
Shipping	natural gas	0

Fuel	Aggregate Sector	Percent
Transportation	natural gas	0
Agriculture-Forestry-Fishing	coal	0
Industry	hard and brown coal	1
Power	hard and brown coal	0
RCO	hard and brown coal	0
Shipping	hard and brown coal	0
Transportation	hard and brown coal	0
Agriculture-Forestry-Fishing	natural gas	0
Industry	diesel and heavy oil	0.5
Power	diesel and heavy oil	0
RCO	diesel and heavy oil	0.5
Shipping	diesel and heavy oil	0
Transportation	diesel and heavy oil	0

8.1.2. Biomass

Residential Biomass

Details regarding historical residential biomass data is detailed in section 3.4 of this supplement.

Industrial Biomass

Industrial Biomass includes biomass used in the following sectors:

- 1A2a_Ind-Comb-Iron-steel
- 1A2b_Ind-Comb-Non-ferrous-metals
- 1A2c_Ind-Comb-Chemicals
- 1A2d_Ind-Comb-Pulp-paper
- 1A2e_Ind-Comb-Food-tobacco
- 1A2f_Ind-Comb-Non-metalic-minerals
- 1A2g_Ind-Comb-Construction
- 1A2g_Ind-Comb-machinery
- 1A2g_Ind-Comb-mining-quarying
- 1A2g_Ind-Comb-other
- 1A2g_Ind-Comb-textile-leather
- 1A2g_Ind-Comb-transpequip
- 1A2g_Ind-Comb-wood-products

Biomass fuel use in industrial sectors is extended with SPEW and population data.

Total biomass used in industrial sectors, per country, is extended from 1970 IEA estimates to 1850 using SPEW data. SPEW provides disaggregated biomass fuel data, but for CEDS all biomass fuels reported by SPEW are aggregated to one CEDS fuel ('biomass').

Industrial Biomass estimates from 1850 - 1970 are disaggregated into CEDS industrial sectors (1A2 sectors) using estimated sector splits. Estimated sector splits are interpolated values between 1850 (where 100% of industrial biomass is in 1A2g_Ind-Comb-other) and the most historical split reported by IEA energy statistics.

Disaggregated industrial biomass estimates are extended back to 1750 using population.

Other Biomass

Other biomass includes biomass used in the following sectors:

- 1A1a_Electricity-autoproducer
- 1A1a_Electricity-public
- 1A1a_Heat-production
- 1A3ai_International-aviation
- 1A3aii_Domestic-aviation
- 1A3b_Road
- 1A3c_Rail
- 1A3dii_Domestic-navigation
- 1A3eii_Other-transp
- 1A4a_Commercial-institutional
- 1A4c_Agriculture-forestry-fishing
- 1A5_Other-unspecified

Total biomass is 'other sectors' is linearly interpolated between the IEA energy statistics estimate in 1971 and 0 in 1850. SPEW estimates that little biomass use in these sectors in 1850.

8.1.3. Other

Waste Combustion

Pulp and paper consumption (FAO 2016) is used to extend waste incineration activity back to 1750.

Other

Activity data for all other sectors is extended to 1750 with on trend population or CDIAC data according to the following table.

Table 5. Other Non-Combustion Activity Extension Drivers

Sector	Historical Extension Proxy
1A1bc_Other-transformation	population

Sector	Historical Extension Proxy
1A3di_Oil_Tanker_Loading	population
1B1_Fugitive-solid-fuels	population
1B2_Fugitive-petr-and-gas	CDIAC liquid and gas fuels
1B2d_Fugitive-other-energy	CDIAC liquid and gas fuels
2A1_Cement-production	population
2A2_Lime-production	population
2Ax_Other-minerals	population
2B_Chemical-industry	2C_Metal-production
population	2D_Degreasing-Cleaning
CDIAC liquid fuels	2D_Paint-application
CDIAC liquid fuels	2D_Chemical-products-manufacture-processing
2D_Other-product-use	population
2H_Pulp-and-paper-food-beverage-wood	population
3B_Manure-management	population
3D_Rice-Cultivation	population
3D_Soil-emissions	population
3E_Enteric-fermentation	population
3F_Agricultural-residue-burning-on-fields	population
3I_Agriculture-other	population
5A_Solid-waste-disposal	population
5D_Wastewater-handling	population
5E_Other-waste-handling	population
6A_Other-in-total	population
6B_Other-not-in-total	population
7A_Fossil-fuel-fires	CDIAC cumulative solid fuels

8.2. Emission Factors

8.2.1. 1850 Combustion Emission Factors

In 1850 the only fuels in our database are coal and biomass, consumed in residential, industrial, and rail sectors. Biomass combustion in the residential sector generally dominates emissions. Emission factors at this time were taken from a literature survey (particularly Winijkul etal 2016), with sector splits from the SPEW database (Bond et al. 2007). As compared to later time periods, combustion temperatures are generally lower, which results in larger CO and lower NO_x emission factors.

Table 6. 1850's Emission factors

Sector	Fuel	Emission	Source and Notes	EF (kg/kg)
1A4_Residential	Biomass	CO	Uncontrolled wood heating EF for heating regions, and GAINS default otherwise	From 0.036 to 0.1154 (AP42 conv woodstove)
1A4_Residential	Coal	CO	Winijkul etal. heating/cooking default EF	0.1622
1A4_Residential	Biomass	NO_x	Winijkul etal. heating EF	0.0001
1A4_Residential	Coal	NO_x	Winijkul etal.	0.0009
1A4_Residential	Biomass	NMVOC	Winijkul etal.	0.0106
1A4_Residential	Coal	NMVOC	Winijkul etal. heating EF	0.0021
1A2_Industry	Coal	NO_x	AP-42 hand-fed units	0.0046
1A2_Industry	Coal	CO	GAINS Global Default	0.0043
1A2_Industry	Coal	NMVOC	GAINS Global Default	0.0017
1A2_Industry	Biomass	NO_x	UK 1970 value	0.0012
1A2_Industry	Biomass	CO	UK 1970 value	0.0726
1A2_Industry	Biomass	NMVOC	UK 1970 value	0.0004
1A3c_Rail	Coal	NO_x	AP-42 hand-fed stoker+	0.0046
1A3c_Rail	Coal	CO	AP-42 hand-fed stoker+	0.1379
1A3c_Rail	Coal	NMVOC	AP-42 hand-fed stoker+	0.0050
All Combustion	All	BC	SPEW	various
All Combustion	All	OC	SPEW	various

+ Value is also very similar to UK 1970s EF

8.3. Process Emissions

8.3.1. 1850’s Process Emissions Assumptions

Most non-combustion emissions, also referred to as process emissions, are small by 1850. The more important emission sectors, and their assumptions:

- SO_2 from non-ferrous metal smelting (estimated as in Smith et al. 2011)
- CO from iron production (scaled back in time using pig iron production statistics)
- NO_x and NH_3 from animal manure (Sector 3B), scaled back from 1970 values using the global trend from Davidson (2009)
- NO_x and NH_3 from fertilized soils (Sector 3D_Soil-emissions), from 1960 - 1970 are extended back with country specific emissions trends for NO_x and NH_3 from synthetic fertilizers and manure according to Davidson (2009). Emission are extended before 1960 with global average per-capita total-N estimates from synthetic and organic fertilizers, also from Holland (2005). This results in small emissions before the mid-20th century.
- NH_3 from human waste (currently both untreated and treated human waste is included in the 5D_Wastewater-handling sector). Consistent with REAS and the EMEP/CORINAIR Guidebook, NH_3 from untreated human waste was assumed to be 1.6 kg/person/year in recent years, with this value declining slightly back to 1850 due to lower nitrogen intake (following Davidson 2009)
- BC and OC from coal coke production are from the latest version of SPEW (Bond et al. 2007).
- Other emissions from coal coke production scaled back from 1970s values using total fossil CO_2 emissions.

8.3.2. CO_2 Other Transformation Assumptions

We have determined that CO_2 emissions from the 1A1bc other transformation sector were underestimated using our default methodology, particularly during the early to mid-20th century. These emissions are largely from production of coal coke, although other coal transformation processes might also contribute. The underestimation occurs because our default methodology for scaling process emissions back in time implicitly assumes the same process efficiency over time. The amount of coal coke needed to produce tonne of pig iron decreased significantly over time (Bond et al. 2007). An adjustment to the CO_2 emissions from the 1A1bc transformation sector was developed to account this effect. This adjustment is similar to that applied to SO_2 emissions, which also exhibited underestimates for a similar reason.

To avoid this underestimation we compute the total CO_2 emissions that we expect, from a mass balance standpoint, to occur from the 1A1bc other transformation sector as:

```
CO2_Conversion = CO2_Coal_Total - CO2_Coal_Combustion - CO2_Coal_NEuse
```

where:

- CO2_Coal_Total is CO_2 emissions from total primary coal consumption, computed using fuel-specific default emission factors. Total coal consumption comes from CEDS extended coal before 1970, and IEA energy statistics from 1971 onwards.
- CO2_Coal_NEuse is CO_2 emissions from coal consumed in non-energy uses, computed using default emission factors. Non-energy coal consumption is from IEA energy statistics, with missing values extrapolated using the formula:

```
IEA_NEuse_coal[fuel, year] = total_coal[year] * IEA_NEuse_coal[fuel, 2007] /
total_coal[fuel, 2007]
```

- CO2_Coal_Combustion is aggregated CO_2 emissions from CEDS combustion emission sectors and coal fuels.

The default coal CO_2 emission factors are the same values computed and used in section "Base Emission Factors/CO_2".

CO_2 other transformation emissions (1A1bc) are then set to be:

```
max(Existing_values, CO2_Conversion)
```

9. Gridded Emissions

The CEDS emissions are spatially allocated on 0.5 degree*0.5 degree resolution over the globe using spatial proxy data by sector. The gridded output is in CF-compliant NetCDF files and spatially referenced using Geographical Coordinate System (lon, lat).

9.1. CEDS Gridding Sectors

The CEDS gridding sectors are provided at two levels: intermediate sector level and final sector level. The intermediate sector level is selected to correspond to the highest level of gridded sectoral detail that we have available from EDGAR. Then the 16 intermediate sectors are aggregated into final sector level which contains 9 sectors. The gridded outputs are provided as in final sector level: bulk emission file contains emissions for 8 sectors (AGR, ENE, IND, TRA, RCO, SLV, WST, and SHP) and a separate file contains emissions for AIR sector.

The table below provides the CEDS intermediate sectors and mappings to final sector level.

Table 7. CEDS Gridding Sectors

Intermediate sector	Intermediate sector abr	Final sector	Final sector abr
Agriculture	AGR	Agriculture	AGR
Electricity and heat production	ELEC	Energy Sector	ENE
Fossil Fuel Fires	FFFI	Energy Sector	ENE
Fuel Production and Transformation	ETRN	Energy Sector	ENE
Industrial combustion	INDC	Industrial Sector	IND
Industrial process and product use	INPU	Industrial Sector	IND

Intermediate sector	Intermediate sector abr	Final sector	Final sector abr
Non-road Transportation	NRTR	Transportation Sector	TRA
Residential, Commercial, Other - Residential, Commercial	RCORC	Residential, Commercial, Other	RCO
Residential, Commercial, Other - Other	RCOO	Residential, Commercial, Other	RCO
Road transportation	ROAD	Transportation Sector	TRA
Solvents production and application	SLV	Solvents production and application	SLV
Waste	WST	Waste	WST
International Shipping	SHP	International Shipping	SHP
Oil and Gas Fugitive/Flaring	FLR	Energy Sector	ENE
Aircraft	AIR	Aircraft	AIR
International Shipping - Tanker Loading	TLOAD	International Shipping	SHP

Table 8. CEDS Gridding Final sectors

Final sector	Description
AGR	Agriculture (non-combustion)
ENE	Energy (production and transformation)
IND	Industry (combustion and process)
TRA	Surface Transportation
RCO	Residential, Commercial, and Other
SLV	Solvents
WST	Waste
SHP	International Shipping
AIR	Aircraft

9.2. General Approach

The CEDS emissions are gridded by country/region and sector. The country/region-sector specified emissions are distributed on normalized spatial proxy data for the country/region. After gridding at this level spatially distributed emissions for all countries/regions are combined into global maps. The emissions in grid cells that contain more than one country/region are adjusted to have portions of emissions from each country/region by using a boundary weighted country/region mask.

The process above is repeated through each sector in the intermediate level then the intermediate level grids are summed into final sector level. Emissions are then distributed over 12 months using spatially-explicit, sector-specific, monthly fractions and converted from mass unit (kt) to flux (kg/m2-s).

9.3. Spatial Proxies

The primary proxy data used in CEDS gridding are from EDGAR gridmaps v4.2 for most of the intermediate sectors as well as ECLIPSE grids for FLR sector and RCP grids for AIR sector. When the primary proxy for a specific country/region, sector, and year combination is not available, CEDS uses gridded population from GPW and HYDE as backup proxy.

The table below describes proxy usage in detail.

Table 9. CEDS proxy data source

CEDS intermediate gridding sector definition	Proxy Data Source	Years
Residential, Commercial, Other	HYDE Population (Decadal values, interpolated annually)	1750 - 1899
	EDGAR v4.2 (1970) blended with HYDE Population	1900 - 1969
	EDGAR v4.2 RCO	1970 – 2008
Agriculture	EDGAR v4.2 AGR	1970 – 2008
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
Industrial Combustion	EDGAR v4.2 INDC	1970 – 2008
Industrial process and product use	EDGAR v4.2 INPU	1970 – 2008
Road Transportation	EDGAR v4.3 ROAD	1750-2014
Non-road Transportation	EDGAR v4.2 NRTR	1970 – 2008
Solvents production and application	EDGAR v4.2 SLV	1970 – 2008
International Shipping	ECLIPSE	1990 - 2010
Waste	HYDE Population, GPW v3 (derived rural population)	1750 – 2014
Oil and Gas Fugitive/Flaring	ECLIPSE FLR 1990, 2000, 2010; EDGAR v4.2 ETRN (1970 - 2008)	1970 – 2010

CEDS intermediate gridding sector definition	Proxy Data Source	Years
Aircraft	CMIP5 (Lamarque et al., 2010; Lee et al., 12)	1850 - 2008

For years before or after the range shown in this table, the spatial proxy is held constant.

9.3.1. Primary Proxy Processing

CEDS uses EDGAR gridmaps v4.2 as its primary proxy data source with several different data sources for specific sectors as described in table 4.

9.3.2. Additional proxy details

Proxy derivation for Waste sector

The Waste sector uses rural population distribution as gridding proxy. Rural area populations are calculated using gridded population based on the definition given by U.S. Department of Health and Human Services that a population density less than 1000 people per square mile. For any grid cell has a population density greater than the 1000 people/sq mile threshold, the population density for that grid cell is fixed to the threshold value, while for any grid cell has a population density less than the threshold, the grid cell keeps its original population density value.

Proxy for Oil and Gas Fugitive/Flaring

The Oil and Gas Fugitive/Flaring sector uses blended ECLIPSE flaring grids and EDGAR v4.2 ETRN grids as gridding proxy. The proxies are blended as 25% of ECLIPSE flaring grid plus 75% of EDGAR v4.2 ETRN grid for the years when both ECLIPSE and EDGAR data are both avaiable and hold constant for years before 1970 and after 2008.

Proxy for Residential, Commercial, Other - Residential, Commercial

For recent years (1970 - 2015), the Residential, Commercial, Other - Residential, Commercial sector uses EDGAR v4.2 RCO grids as gridding proxy (proxy is held constant after 2008). For years form 1900 to 1969, the sector uses linearly blended EDGAR v4.2 RCO grids with HYDE gridded population as gridding proxy. And for years before 1900, the HYDE gridded populations was used as proxy for gridding.

Proxy for International Shipping

The International Shipping sector uses ECLIPSE shipping grids as gridding proxy (http://www.iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv5.html). The ECLIPSE shipping grids are provided for years from 1990 to 2015 at 5 years interval. For years before 1990 the proxy is held constant as year 1990 grids.

Special routine for NMVOC International Shipping emissions gridding

For NMVOC, the shipping grid has two components — a sub grid for international shipping emissions and a sub grid for tanker loading emissions. The international shipping sub grid has been generated just the same as other emissions species using proxies listed in the table. But the sub grid for tanker loading emissions is generated using a proxy derived from S50_VOC_1x1_1yr_1996_VERITAS.dat. Afterwards, two sub grids are combined into final shipping grid.

The magnitude of tanker loading evaporative emissions is taken from the IMO GHG study (2014) scaled by crude oil transport from UNCTAD until 1970, then by CDIAC total CO_2 from petroleum before 1970.

CO_2 proxy substitution

For CO_2, the CEDS gridding routine uses EDGAR v4.2 CO_2 grids as spatial proxy for all sectors except Non-Road Transportation, Aircraft, and International Shipping. For above three sectors the NO_X gridding spatial proxies are used for CO_2 gridding.

9.3.3. Proxy Substitution Check

A check is made for each country to see if adequate primary proxy data is available for each emission species/country/region-sector-year combination. If a country's/region's spatial proxy is very small or zero for that year/sector (relative to other countries/regions), the backup proxy (generally population) will be used. In order to decide whether primary proxy is suitable or not for specific country/region-sector-year emissions been gridded, a proxy substitution check is performed during gridding process.

9.3.4. Backup Proxy Processing

Gridded population from HYDE and GPW are pre-processed and used as CEDS gridding backup proxies. The original HYDE gridded population data are provided by PBL Netherlands Environmental Assessment Agency for year 1750 to 1990 at 10 years interval. These data are then processed and interpolated to yearly data and used as backup proxy in CEDS for year 1750 to 1899. The original GPW gridded population data are provided by the Center for International Earth Science Information Network, Columbia University for year 1990 to 2000 at 5 years intervals. There data are then processed and interpolated to yearly data and used in CEDS for year 1990 to 2000. For years after 2000, gridded populations are duplicates of GPW 2000 gridded population.

9.4. Seasonality Profile

During the process of gridding, emissions are distributed over 12 months using spatially distributed ratios that reflect monthly emission variations by sector. The monthly fraction used in CEDS are from ECLIPSE project, http://eclipse.nilu.no/. and are currently constant in time. There is currently no seasonality profiles for sector Fuel Production and Transformation, Road Transportation, Residential, Commercial, Other - Other, Solvents Production and Application, and Waste. Specifily when apllying seasonality profiles for emissions, the CEDS gridding system takes 'noleap' year assumption that assume for every grdding year the number of days is 365 with 28 days in February.

The table below describes detailed use of seasonality profiles in CEDS.

Table 10. CEDS seasonality profile use

sector	Seasonality profile
AGR	monthly fraction from ECLIPSEv5_monthly_patterns; separate monthly fraction (also from ECLIPSEv5_monthly_patterns) for NH_3
ELEC	monthly fraction from ECLIPSEv5_monthly_patterns
FFFI	monthly fraction from ECLIPSEv5_monthly_patterns
ETRN	monthly fraction from ECLIPSEv5_monthly_patterns
INDC	monthly fraction from ECLIPSEv5_monthly_patterns
INPU	monthly fraction from ECLIPSEv5_monthly_patterns
NRTR	constant monthly fraction from ECLIPSEv5_monthly_patterns
RCORC	monthly fraction from ECLIPSEv5_monthly_patterns
RCOO	constant monthly fraction
ROAD	constant monthly fraction from ECLIPSEv5_monthly_patterns
SLV	constant monthly fraction
WST	constant monthly fraction
SHP	monthly fraction from EDGAR PEG_TNR_SHIP
FLR	monthly fraction from ECLIPSE_V5a_CLE_base_flaring
AIR	monthly fraction from RCP
TLOAD	-

9.5. VOC Speciation

The approach taken for VOC speciation follows that for HTAPv2, http://iek8wikis.iek.fz-juelich.de/HTAPWiki/WP1.1, using country and sector-specific speciation profiles originally developed for the RETRO project.

9.5.1. Extraction of speciation profiles

Speciation profiles by country and sector were extracted from the 0.5 degree RETRO files. 23 Retro files presenting 23 individual VOCs emission ratios to total NMVOC emission for 8 anthropic emission sectors were used for extraction. The country-sector specific ratios then were extracted from a cell which (a) presents the speciation data and (b) is the maximum ratio value within the country. In addition, under the assumption of that all RETRO individual VOC ratios sums to 1 in all cells, all 23 extracted ratios for one particular country and sector should add up to 1 if using the same cell for every sub-species ratio extraction.

9.5.2. International shipping sector speciation profile

Individual VOCs emission ratios to total NMVOC emission for international shipping sector and oil tanker loading are provided by Eyring et al. 2005, Table 2.

10. Known Issues

- Fossil fuel consumption for countries included in IEA "other countries" categories (e.g. "Other Asia", "Other Africa", and "Other Non-OECD Americas") were disaggregated using population. Emissions for the constituent countries may, therefore, may not reflect actual fuel use in these countries. In particular emissions for some of these countries for SO_2, BC, and OC, which are not calibrated to EDGAR, may be in-consistent with other emissions. For this reason we have distributed emissions in aggregate form for these countries (with this caveat, the more disaggregated emissions are available on request). This does not have a signifiant large impact on overall emissions, and we plan to improve this in future versions.
- IEA "other countries" sometimes have spurious sector splits due to the simple methods used to assign fuel use to these countries (e.g. Afghanistan international shipping).
- There are 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%) and will not have a signifiant impact on simulation results.
- 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.
- A data processing error was discovered in the estimation of emissions seasonality for the CMIP6 gridded emissions data. This results in a slight distortion of emissions seasonality in the gridded emission files for some sectors and species (such as small increase in February fluxes over the correct calculation). A multiplicative correction grid is being developed and will be distributed by the project.

11. References

- Andres, R. J., Fielding, D. J., Marland, G., Boden, T. A., Kumar, N. and Kearney, A. T.: Carbon dioxide emissions from fossil-fuel use, 1751–1950, Tellus 51B, 51(4), 759–765, 1999.
- Australian Department of the Environment: National Pollutant Inventory (NPI), Canberra, Australia. [online] Available from: http://www.npi.gov.au/substances, 2016.
- Bartoňová, L. (2015) Unburned carbon from coal combustion ash: An overview. Fuel Processing Technology, 134, 136-158.
- Bond, T. C., et al. (2007). "Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850-2000." Global Biogeochemical Cycles 21(2).

- Blumberg, Katherine O., Michael P. Walsh, and Charlotte Pera. (2003). "Low-sulfur gasoline & diesel: the key to lower vehicle emissions."
- Boden, T.A., G. Marland, and R. J. Andres. (1995). Estimates of global, regional, and national annual CO_2 emissions from fossil-fuel burning, hydraulic cement production, and gas flaring: 1950-1992. ORNL/CDIAC-90, NDP-30/R6. Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee.
- Carbon Dioxide Information Analysis Center (CDIAC). “Carbon Dioxide Information Analysis Center - Conversion Tables. Table 6. Factors and Units for Calculating Annual CO_2 Emissions Using Global Fuel Production Data.” (Accessed August 2016) http://cdiac.ornl.gov/pns/convert.html#6.
- Denier van der Gon, H. A. C., et al. (2015) "Particulate emissions from residential wood combustion in Europe–revised estimates and an evaluation." Atmospheric Chemistry and Physics 15.11, 6503-6519.
- Davidson, E. A. (2009). The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. Nature Geoscience, 2(9), 659-662.
- EC-JRC/PBL: Emission Database for Global Atmospheric Research (EDGAR), release version 4.3.1. [online] Available from: http://edgar.jrc.ec.europa.eu/overview.php?v=431, 2016.
- Endresen, Ø., Sørgard, E., Behrens, H.L., Brett, P.O., and Isak- sen. (2007). “I.S.A.: A historical reconstruction of ships’ fuel consumption and emissions”. J. Geophys. Res., 112, D12301, doi:10.1029/2006JD007630.
- Environment Canada: Sulfur in Liquid Fuels 2005. [online] Available from: http://publications.gc.ca/site/archivee-archived.html?url=http://publications.gc.ca/collections/collection_2014/ec/En11-6-2005-eng.pdf, 2016.
- Environment Canada: National Emission Trends for Key Air Pollutants, 1985-2011. [online] Available from: http://www.ec.gc.ca/inrp-npri/default.asp?lang=en&n=0EC58C98-#sommaires, 2013.
- Energy Information Administration (2013). "U.S. Total Adjusted Sales of Distillat Fuel Oil by End Use." Web. http://www.eia.gov/dnav/pet/pet_cons_821dsta_dcu_nus_a.htm.
- Eyring, V., H. W. Ko¨hler, J. van Aardenne, and A. Lauer (2005), Emissions from international shipping: 1. The last 50 years, J. Geophys. Res., 110, D17305, doi:10.1029/2004JD005619.
- Eyring, V., Isaksen, I.S.A., Berntsen, T., Collins, W.J., Corbett, J.J., Endresen, O., Grainger, R.G., Moldanova, J., Schlager, H., Stevenson, D.S., 2010. Transport impacts on atmosphere and climate: Shipping. Transp. Impacts Atmosphere Clim. ATTICA Assess. Rep. 44, 4735–4771. doi:10.1016/j.atmosenv.2009.04.059
- Fernandes, S.D., et al. (2007) "Global biofuel use, 1850–2000." Global Biogeochemical Cycles 21.2.
- Fletcher, M. E. (1997). “From coal to oil in British shipping” in: Williams, David, M., The World of Shipping, by Aldershot, Hants, England, Ashgate, Brookfield VT.
- Foell. W., M. Amann, G. Carmichael, M. Chadwick, J. Hettelingh, L., Hordijk and Z. Dianwu (eds.) (1995). “RAINS- Asia: An Assessment Model For Air Pollution In Asia”.
- FAO. Forest product statistics. (Accessed June 2016) http://www.fao.org/forestry/statistics/en/.
- Fouquet, R. and P.J.G. Pearson (1998). “A thousand years of energy use in the United Kingdom”.

The Energy Journal 19(4) 1-41.

- Gschwandtner, Gerhard, et al. (1985). "Historic emissions of sulfur and nitrogen oxides in the United States from 1900 to 1980." v2.
- Holland, E. A., Lee-Taylor, J., Nevison, C. and Sulzman, J. M.: GLOBAL N CYCLE: FLUXES AND N2O MIXING RATIOS ORIGINATING FROM HUMAN ACTIVITY. [online] Available from: http://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=797 (Accessed 12 January 2017), 2005.
- Huo, H., Lei, Y., Zhang, Q., Zhao, L. & He, K. 2012. China's coke industry: Recent policies, technology shift, and implication for energy and the environment. Energy Policy, 51, 397-404.
- IIASA: GAINS - Sulfur Content of Fuels, , doi:Scenario: TSAP_Consultation_2014, 2014a.
- IIASA: GAINS - Sulfur Retention in Ash, , doi:Scenario: TSAP_Consultation_2014, 2014b.
- International Energy Agency (2016) CO_2 Emissions from Fuel Combustion: 2016 Edition. (IEA, Paris, France, ISBN 978-92-64-25856)
- IMO (2014). "Reduction of GHG Emissions From Ships: Third IMO GHG Study 2014" (MEPC-67-6-INF3-2014).
- Kaur, R., Wani, S. P., Singh, A. K., & Lal, K. (2012). Wastewater production, treatment and use in India. In National Report presented at the 2nd regional workshop on Safe Use of Wastewater in Agriculture. (Accessed June 2016) http://www.ais.unwater.org/ais/pluginfile.php/356/mod_page/content/111/CountryReport_India.pdf
- Kholod, N., and Evans, M. (2015). "Circumpolar Best Practices: Policy and Financing Options for Black Carbon Emission Reductions from Diesel Sources".
- Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., Borken-Kleefeld, J., and Schöpp, W.: Global anthropogenic emissions of particulate matter including black carbon, Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-880, in review, 2016
- Kurokawa, J., Ohara, T., Morikawa, T., Hanayama, S., Janssens-Maenhout, G., Fukui, T., Kawashima, K. and Akimoto, H.: Emissions of air pollutants and greenhouse gases over Asian regions during 2000–2008: Regional Emission inventory in ASia (REAS) version 2, Atmospheric Chem. Phys., 13(21), 11019–11058, 2013a.
- Kurokawa, J., Ohara, T., Morikawa, T., Hanayama, S., Janssens-Maenhout, G., Fukui, T., Kawashima, K. and Akimoto, H.: Emissions of air pollutants and greenhouse gases over Asian regions during 2000–2008: Regional Emission inventory in ASia (REAS) version 2, Atmospheric Chem. Phys., 13(21), 11019–11058, doi:REAS ver 3 preliminary version-20150112, 2013b.
- Li, M., Zhang, Q., Kurokawa, J., Woo, J.-H., He, K., Lu, Z., Ohara, T., Song, Y., Streets, D. G., Carmichael, G. R., Cheng, Y., Hong, C., Huo, H., Jiang, X., Kang, S., Liu, F., Su, H. and Zheng, B.: MIX: a mosaic Asian anthropogenic emission inventory under the international collaboration framework of the MICS-Asia and HTAP, Atmospheric Chem. Phys., 17(2), 935–963, doi:10.5194/acp-17-935-2017, 2017.
- Liu, F., Zhang, Q., Tong, D., Zheng, B., Li, M., Huo, H., and He, K. B.: High-resolution inventory of technologies, activities, and emissions of coal-fired power plants in China from 1990 to 2010, Atmos. Chem. Phys., 15, 13299-13317, doi:10.5194/acp-15-13299-2015, 2015.
- Liu, Z. et al. (2015). Reduced carbon emission estimates from fossil fuel combustion and cement production in China.
- Ludek, Holub et al. (2005). "The Century of Petrol - The History Of The Refining Industry In The

Czech Lands”.

- Mclinden, C. A., Fioletov, V., Shephard, M. W., Krotkov, N., Li, C., Martin, R. V., Moran, M. D. & Joiner, J. 2016. Space-based detection of missing sulfur dioxide sources of global air pollution. Nature Geosci, 9, 496-500.
- Mester, Z. C. (2000) "Meeting sulfur specifications for 2000 and beyond." San Francisco: 26-29.
- Mitchell, B.R. (1998c). International historical statistics: Europe, 1750-1993.
- Mylona, S. (1996). “Sulphur dioxide emissions in Europe 1880–1991 and their effect on sulphur concentrations and depositions”.
- Olivier JGJ, G. Janssens-Maenhout, M. Muntean, J.A.H.W. Peters (2015), Trends in global CO_2 emissions; 2015 Report, The Hague: PBL Netherlands Environmental Assessment Agency; Ispra: European Commission, Joint Research Centre
- OECD Waste water treatment (indicator). doi: 10.1787/ef27a39d-en. (Accessed on 23 March 2016) https://data.oecd.org/water/waste-water-treatment.htm
- Pretorius, I., Piketh, S., Burger, R. and Neomagus, H.: A perspective on South African coal fired power station emissions, J. Energy South. Afr., 26(3), 27–40, 2015.
- Rowe, Johanna (Morrison) (1999) “Heart of a Mountain, Soul of a Town: the story of Algoma Ore and the town of Wawa" (privately published, Wawa, Ontario, 1999), p 121. Accessed on line: http://www.ourroots.ca/e/page.aspx?id=910392
- Ryaboshapko, A.G., Brukhanov, P.A. , Gromov, S.A., Proshina, Y.V., and Afinogenova, O.G., Anthropogenic emissions of oxidized sulfur and nitrogen into the atmosphere of the former Soviet Union in 1985 and 1990, Department of Meteorology, Stockholm University, Report CM-89, 1996.
- Say, N. P. (2006) "Lignite-fired thermal power plants and SO_2 pollution in Turkey" Energy Policy 34 2690–2701
- Sanger, R. P et al. (1997). “Motor Vehicle Emission Regulations and Fuel Specifications - Part 2: Detailed Information and Historic Review (1970 -1996).” (Accessed September 2015) https://www.concawe.eu/uploads/Modules/Publications/2002-00203-01-e.pdf.
- Simachaya, W. (2015). Thailand’s Coal-fired Power Plant Pollution Control. (Accessed March 2016) https://eneken.ieej.or.jp/data/6467.pdf
- Smith, SJ, J van Aardenne, Z Klimont, R Andres, AC Volke, and S Delgado Arias. (2011) “Anthropogenic Sulfur Dioxide Emissions: 1850-2005”. Atmos. Chem. Phys., 11, 1101–1116.
- Smith, T. W. P., Jalkanen, J. P., Anderson, B. A., Corbett, J. J., Faber, J., Hanayama, S., O’Keeffe, E., Parker, S., Johansson, L., Aldous, L., Raucci, C., Traut, M., Ettinger, S., Nelissen, D., Lee, D. S., Ng, S., Agrawal, A., Winebrake, J. J., Hoen, M., Chesworth, S., Pandey, A. (2014). Third IMO GHG Study 2014, International Maritime Organization (IMO) London, UK. (Accessed 2016) http://www.cedelft.eu/?go=home.downloadPub&id=1525&file=MEPC-67-6-INF3-2014-Final-Report-complete_1438780969.pdf
- South Korea National Institute of Environmental Research: National Air Pollutants Emission Service. [online] Available from: http://airemiss.nier.go.kr/, n.d.
- Stohl, A., et al. (2015). "Evaluating the climate and air quality impacts of short-lived pollutants." Atmos. Chem. Phys. 15(18): 10529-10566.

- TEPA: Taiwan Emission Data System. [online] Available from: teds.epa.gov.tw/, 2016.
- Tushingham, M. (1996). "Regional Composition of Gasoline and Diesel".
- UK DEFRA: National Atmospheric Emissions Inventory (NAEI): Emissions of Air Quality Pollutants 1990-2013. [online] Available from: http://naei.defra.gov.uk/reports/reports?report_id=853, 2015.
- UN Environmental Indicators, Inland Water Resources. (Accessed May 2016) http://unstats.un.org/unsd/environment/wastewater.htm
- UN Sanitation Country Profile: Russian Federation. (Accessed May 2016) http://www.un.org/esa/agenda21/natlinfo/countr/russia/RussiaSanitation04f.pdf
- UNFCCC: Argentinian Invenotory 1990 - 2012, Submitted to UNFCCC., 2016.
- UNFCCC: National Inventory Submissions of Annex I Parties to the UNFCCC. [online] Available from: http://unfccc.int/, 2015.
- United States. Congress., et al. (2012). "Report to Congress On Black Carbon: Department of the Interior, Environment, and Related Agencies, Appropriations Act, 2010." Research Triangle Park, NC: U.S. Environmental Protection Agency, Office of Air and Radiation, Office of Air Quality Planning and Standards.
- U.S. Department of Commerce - The Bureau of the Census (1975). Pig Iron Shipments 1799 - 1970.
- US EPA: 2011 National Emissions Inventory (NEI) v2. [online] Available from: https://www.epa.gov/air-emissions-inventories/2011-national-emissions-inventories (Accessed 24 August 2016), 2013.
- US EPA: EPA report: EPA 430-R-15-004: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2013, U.S. Environmental Protection Agency, 200 Pennsylvania Ave., N.W. Washington, DC 20460, U.S.A., 2015.
- US EPA (2005). "National Emission Trends - Updated 7/18/2005: Sulfur Dioxide Emissions." Web.
- Wang, S. X., Zhao, B., Cai, S. Y., Klimont, Z., Nielsen, C. P., Morikawa, T., Woo, J. H., Kim, Y., Fu, X., Xu, J. Y., Hao, J. M., and He, K. B.: Emission trends and mitigation options for air pollutants in East Asia, Atmos. Chem. Phys., 14, 6571-6603, doi:10.5194/acp-14-6571-2014, 2014.
- Wiedinmyer C., Yokelson R. J., Gullett B. K. (2014). "Global emissions of trace gases, particulate matter, and hazardous air pollutants from open burning of domestic waste." Environ. Sci. Technol. 2014, 48, 9523_9530.
- Winijkul, E, L. Fierce, T.C. Bond (2016) Emissions from residential combustion considering end-uses and spatial constraints: Part I, methods and spatial distribution, Atmospheric Environment 125, 126–139.
- Wu, Q. R., Wang, S. X., Zhang, L., Song, J. X., Yang, H. & Meng, Y. 2012. Update of mercury emissions from China's primary zinc, lead and copper smelters, 2000 - 2010. Atmos. Chem. Phys., 12, 11153-11163.
- Zhou, Y., Chang, C. C., Ni, Y., Li, J., Wei, S., & Zhang, Y. (2011). Status and development for municipal wastewater reuse in China. In Water Resource and Environmental Protection (ISWREP), 2011 International Symposium on (Vol. 4, pp. 3183-3186). IEEE.
- (For diesel standards) Vehicle Emission Reductions (ECMT 2001); UNEP data sheets;

www.dieselnet.com; http://www.crc.cz/en/diesel-oil.aspx