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Open Access Earth System Science Data Discussions

Updated historical (1750 – 2023) trends of reactive gases and aerosols from the Community Earth atmospheric Data System (CEDS)

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Abstract. Estimates of anthropogenic air pollutants and reactive gases remain essential for air quality, weather and other earth systems modeling. Here we present an updated historical time series (1750 – 2023) produced by the Community Earth atmospheric Data System (CEDS), version CEDS v_2025_03_18, which is widely used in national and international models and modeling exercises. This dataset provides historical estimates of anthropogenic chemically reactive atmospheric gases (carbon monoxide - CO, methane - CH_4, ammonia - NH_3, nitrogen oxides - NO_X, sulfur dioxide - SO_2, and non-methane volatile organic compounds - NMVOCs), carbonaceous aerosols (black carbon – BC, and organic carbon – OC), as well as carbon dioxide - CO_2 and nitrous oxide - N_2O. Aggregate annual estimates are available by 220 countries, 62 sectors, and 8 fuels (in addition to process emissions). Gridded data are available for 9 final gridding sectors with monthly seasonality and VOC speciation in netcdf v4 (HDFv5) format with CF-compliant metadata at 0.5-degree resolution for the full time series and downscaled to 0.1 degree from 1980 forward.

1 Introduction

Accurate, timely emissions estimates are essential for air quality, weather, and other earth systems modeling and many varied data sets exist to meet the needs of the diverse earth systems modeling community, spanning time periods, geographical coverage, and level of detail. There are several global research inventories estimating air pollutants and greenhouse gases overtime that are widely used by the earth systems modeling community, each prioritizing different data elements. The Emissions Database for Global Atmospheric Research (EDGAR) (European Commission, Joint Research Centre (EC-JRC) 2024b, 2024a) focuses on independent estimates with country specific data from 1970, which are regularly updated to most recent years. The Hemispheric Transport of Air Pollution (HTAPv3 and HTAPv3.1) (Crippa et al. 2023; Guizzardi et al. 2025) takes a mosaic approach to compile global air pollutant emissions over the past 2 decades, integrating official country and regional inventories with high spatial and temporal resolution. The Copernicus Atmospheric Monitoring Service global anthropogenic emissions inventory (CAMS-GLOB-ANT) (Soulie et al. 2024) provides spatially and monthly resolved estimates for 17 detailed sectors from 2000 onward, focusing on recent near real-time data. The Greenhouse Gas and Air Pollution

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Interactions and Synergies Model (GAINS) (Amann et al. 2011) – is an integrated analysis platform focusing on emissions controls, policy analysis, and more detailed technologies. While GAINS produces historical emissions estimates as the other data sets mentioned here, it also projects policy scenarios into the future in 5-year timesteps.

The Community Earth atmospheric Data System (CEDS) (formerly the Community Emissions Data System) is unique from these inventories in that it is focused on readily updatable, consistent trends, over long time-horizons. CEDS, however, is not an entirely independent inventory and relies heavily on other existing data sets, particularly EDGAR and GAINS. CEDS incorporates country specific inventory data at various levels of specificity, where available, while maintaining detailed trends overtime, and extends activity and emission factor components back in time separately to construct consistent historical trends. CEDS was first used as the historical anthropogenic forcing data set in the Coupled Model Intercomparison Project 6 (CMIP6) (R. M. Hoesly et al. 2018) and subsequently updated in 2020 (McDuffie et al. 2020), 2021(O'Rourke et al. 2021), and 2024 (R. Hoesly et al. 2024). This paper describes the general methodology and results for the updated release of CEDS for use in CMIP7, CEDS v_2025_03_18. More detailed methodology can be found in Hoesly et al. (2018).

CEDS estimates sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), carbon monoxide (CO), black carbon (BC), organic carbon (OC), non-methane volatile organic compounds (NMVOCs), carbon dioxide (CO_2) from 1750 – 2023, as well as methane (CH_4) and nitrous oxide (N_2O) from 1970 forward with a supplementary, simplified historical extension to 1750. While SO_2 and CO_2 estimates are largely independent of other global inventories (see below), other emission species rely heavily on other estimates and should not be considered independent estimates.

Aggregate annual country estimates, CEDS v_2025_03_18, are available via zenodo (R. Hoesly et al. 2025a). Gridded data, CEDS v_2025_04_18, are released on Earth System Grid Federation (ESGF) at 0.5 degree along with 0.1-degree downscaled data for recent years (1980 – 2023). This inventory is estimated using the data system, which is fully open source (except proprietary energy data, see below) and available at https://github.com/JGCRI/CEDS.

An overview of the methodology and data sources is provided in section 2, with additional details available in the supplement, outlined in section 2.7. Section 3 and 4 review the data trends and compares to other inventories, Section 5 presents an analysis using this data in a simple climate model, Section 6 discusses uncertainty in the data, and Section 7 discusses future work planned for CEDS. Throughout this paper we will reference the locations of files within the data system. The supplement, detailed in Section 9, includes an explanation of how to navigate the data system to further understand data sources and assumptions.

2 Data and Methodology

2.1 Methodology Overview

CEDS uses existing energy data, other activity and driver data, emission factors, and emissions inventories, to estimate country-, sector-, and fuel-specific emissions trends in six major stages:

1. Energy and Driver Data: energy and other driver data, such as population and industrial activity, are collected and corrected (Section 2.2)

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2. Default Estimates in the Modern Era: default emissions from 1960/1971 through 2023 are estimated using default emission and emissions factor data
3. Estimate Scaling: aggregate estimates are scaled to match country specific inventories where available and plausible, then disaggregated back to CEDS level detail (Section 2.4)
4. Historical Extension: historical activity data and emissions factors are extended back to 1750 using proxy data (Section 2.5)
5. Summary: final emissions data are checked and summarized for release and analysis
6. Gridding: gridded emissions with monthly seasonality and monthly VOC speciation are estimated using proxy data along with emission information for large SO_2 point sources (Section 2.6)

Rather than producing fully independent estimates, CEDS relies on existing data and matching to reliable inventories at an aggregate level, then extends values to historical years. Unlike other existing inventories that use mosaic strategies to stitch together regional data into a global inventory, such as HTAP, CEDS combines data at various aggregation and time scales to produce consistent trends overtime.

CEDS produces estimates for 62 sectors, 220 countries (including a global region for international shipping and aircraft) and 8 fuels in addition to process emissions. Sector definitions are largely derived from sector/flow definitions from International Energy Agency (IEA) World Energy Statistics for combustion emissions and from EDGAR for process emissions, two foundational datasets used to produce CEDS estimates, along with NFR-14 nomenclature. More detail on sector, fuel, and country definitions can be found in the supplement.

CEDS does not include open biomass burning emissions. Documentation of CMIP7 open biomass burning emissions and other forcing data sets can be found at https://input4mips-cvs.readthedocs.io.

While many unique datasets are used for estimating each emissions species, one or two foundational data sets are often used to make up the bulk of default emissions estimates for an emission species or sector. BC and OC emissions are estimated largely from the Speciated Pollutant Emission Wizard (SPEW) (Bond et al. 2007) and GAINS. Base combustion emissions factors for other species are often estimated from GAINS. Agricultural emissions are estimated from the Food and Agriculture Organization (FAO) (FAO 2023). NO_X, CO, NH_3, and NMVOC are estimated from EDGAR. SO_2 and CO_2 emissions don't draw as heavily from other global inventories and are instead derived from data on fuel properties (carbon content and sulfur content) and mitigation efforts. As such, CEDS SO_2 and CO_2 estimates are much more independent from other inventories than CEDS estimates for other emission species.

An overview of CEDS methodology is given here, but more detail can be found in Hoesly et al. (2018) and in the full data system.

2.2 Activity Data

2.2.1 Energy Data

Energy consumption data is used to drive combustion sector emissions. Primary energy data for combustion sectors in the modern era (1961 and 1971 for OECD and non-OECD nations respectively) is from the IEA World Energy

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Statistics (IEA 2024). This is proprietary data, available by license and is required to run the data system and generate CEDS final emission factors. IEA energy flows and products are mapped (and sometimes aggregated) to CEDS working sectors and fuels and detailed in Hoesly et al. (2018). Data for some small countries are sometimes provided by IEA in aggregate, for example "Other Asia or "Other Africa". This data is disaggregated to country level by aggregate fuel using historical CO_2 emissions from Carbon Dioxide Information Analysis Center (CDIAC) and sometimes population. Data from the Former Soviet Union (FSU) is also smoothed to account for methodology changes in energy accounting during the transition to independent countries.

IEA energy data is extended from the last IEA year (2022) to the most recent year (2023) using the Energy Institute (EI) Energy Statistics (Energy Institute 2024), formerly the British Petroleum Statistical Review of World Energy. EI energy data is more aggregate, available only for larger countries or regions and aggregate fuel. More detailed fuel type data is provided for petroleum fuels. The more detailed IEA data are extended with these aggregate trends. More details on IEA to CEDS sector and fuel mappings are available in the supplement and data system.

In some cases, energy data is corrected, smoothed, or reassigned among sectors. Some of these corrections include smoothing a spike in agricultural diesel consumption in Canada in 1984; zeroing out spurious brown coal consumption in Other Asia from 1974 to 1981; smoothing discontinuities in residential biomass to better capture earlier stages of energy transition from 1971 to 2014 in a number of countries (new in this version: Ghana, Indonesia, South Africa, and Vietnam); smoothing out discontinuities in reported residential biomass to join historical estimates for per capital rural wood consumption in Canada and the USA; extrapolating residential biomass in Bosnia and Herzegovina to match Pfeiffer et al. (2019); corrections for USA off road diesel, gasoline, and kerosine in the USA to produce more consistently time series. More detail on these corrections can be found in the data systems in input/energy/energy-data-adjustments.

2.2.2 Non-Combustion (process) Sector Driver Data

Consistent historical trend data is prioritized for non-combustion driver data. In non-combustion sections (most non-1A sectors) where energy consumption data is not used, population is often used as a scalar or activity indicator to extend historical trends, particularly for earlier years where sector-specific driver data is not available. Population trends used in CEDS are derived from combining UN population data (UN 2014, 2015), World Bank population statistics (World Bank 2016), and HYDE historical population data (Klein Goldewijk et al. 2010). More details on these methods are given in section 2.1 of the supplement of Hoesly et. al. (2018).

Sectoral activity drivers are used where available, notably using non-combustion emission trends from EDGAR from 1970 forward as our default data, but from other sources (e.g., oil production, metal smelting) where data is available. Sectors driven by other data include 2C3_Aluminum-production, 2C1_Iron-steel-alloy-prod, and 5C_Waste-incineration, where aluminum production, pig iron production, and pulp and paper consumption, respectively, are used instead.

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2.3 Default Emission Estimates

Default estimates serve as a starting calibration point from which to scale to country inventories. While many of the default values do not appear in the final emissions database, as many estimates are scaled to country inventories (Section 2.4), effort is spent to develop accurate defaults, including abatement measures, so that the calibration scaling is small, particularly for the earliest years of the calibration data used. Default estimates also serve to disaggregate scaled emissions (at an aggerate level) back to CEDS level detail. Some default emissions appear in the final data set where reliable inventories are not available or for CO_2, where default combustion emission factors are more reliable (with less country-specific variation) than for other emission species.

While each sector and region's default data are estimated using unique data and sometimes varying methodology, defaults are generally calculated from emission, emissions factor, and activity data, as shown in (1.

$$E_{em}{}^{c,s,f,t} = EF_{em}{}^{c,s,f,t} \times A^{c,s,f,t} \,, \tag{1}$$

where E is total emissions, EF is the emission factor, A is the activity driver, c is country, s is sector, f is fuel (when applicable), and t is year.

2.3.1 Combustion

Default emissions for combustion sectors (1A) are estimated according to (1 from IEA energy data and a set of default emissions factors for each emission species from many sources. Default combustion emission factors are largely from foundational data sets such GAINS model and The Speciated Pollutant Emission Wizard (SPEW) for BC/OC. However, some default estimates are estimated directly from activity data, fuel properties (e.g. sulfur content for SO_2 emissions) and abatement measures. Sometimes default emission factors trends are modified to better match scaling inventories in an iterative process. More detail on specific data used for default estimates can be found in section 2.3 of Hoesly et al (2018) and in the data system under input/default-emissions-data.

2.3.2 Non-Combustion

Default non-combustion emissions are also largely estimated from existing inventories, where default emissions are taken from EDGAR estimates using population or other activity data as a scalar to extend emissions estimates to additional year as discussed in §2.2.2. While emissions from 1A1bc-Other_transformation are also from the combustion of fuel, this sector is treated as non-combustion sector due to its complexity and is, at this time, driven with population data for years outside of EDGAR range. For BC and OC, trends are from SPEW.

In some cases, default non-combustion emissions were several orders of magnitude different than emission reported in national inventories. In these cases, default non-combustion emissions were taken directly from the national inventories and gap filled and extended over the time-period using EDGAR. This is most common for flaring (1B), waste (5), soil (3D), and NMVOCs associated with solvent use. Details on these exceptions can be found in the data system, under input/default-emissions-data/non-combustion-emissions. More detail on non-combustion estimates can be found in section 2.3.2 of Hoesly et al (2018) and in the data system.

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2.4 Scaling Default Emission Estimates to Inventories

CEDS emissions scaling technique is a unique and foundational approach compared to other inventories. Where reliable national inventories exist, CEDS's goal is to match emissions at an aggregate level while maintaining CEDS sector and fuel level detail. While CEDS scaling alters default emissions and emissions factors, resulting in scaled emission factors and scaled emissions, activity drivers remain the same. For each national inventory, common aggregate scaling sectors are defined so that CEDS sectors and national inventory sectors can be aggregated up to the scaling sector level, resulting in 2 comparable sets of aggregate scaling sectors. CEDS emissions are altered and matched to the national inventory values at the scaling sector level, then disaggregated back to the CEDS sector and fuel detail using the proportions from the default CEDS emissions by sector and fuel. CEDS scaled emission factors are inferred from scaled emissions and activity data.

CEDS scales with aggregate sectors to better assure that the sectoral definitions and underlying energy consumption data are comparable between CEDS and the country inventory. If scaling occurred at a more detailed level of sectoral resolution, sector definition mismatches could result in unrealistic emission factors. Sometimes scaling to inventories, even when reliable, is not possible as the energy statistics in the national inventories are divergent from CEDS energy drivers, yielding skewed scaled emissions and emissions factors. In these cases, CEDS defaults are maintained. This is very common for off-road emissions, for example.

Several specific corrections are applied to emission factors and activity data in the USA and Canada to account for additional detailed data available for these countries. For the United States, EPA air pollutant emission trends data, released annually, is used as the primary inventory data. Artificial discontinuities in this data are present due to changes in methodologies over time. Before use in CEDS these discontinuities are smoothed over, most often favoring the more recent estimates in the time series. Several emission sub-sectors were re-estimated going back in time for long-term consistency, including emissions from wood used in residential heating (introducing decreases in emission factors due to the introduction of wood stove emission standards since 1985), and non-energy recreational use of wood (backyard firepits, etc.), and BC/OC from commercial cooking. Emissions from these sectors will now differ somewhat from the original EPA inventory.

For both Canada and the USA gasoline use for off-road engines is subtracted from IEA road consumption and added to the *1A5_Other-unspecified* sector, with emission factors, particularly for CO, for off road use adjusted to match inventory data. CO emissions in both countries now better match inventory trends. This indicates that global inventories using reported fuel consumption from the road sectors without adjusting for off-road use can result in biased emission estimates. These, and additional adjustments, are documented in metadata files in the data system release.

An additional layer of scaling has been added to account for a mismatch in the underlying energy data in the current versions of EDGAR air pollutants (EDGAR v8.1 API) and CEDS. This version of CEDS often has significant differences in biomass consumption as compared to the version of the IEA data used for EDGAR. This is because of both use of the newer IEA energy statistics in CEDS and corrections to IEA biomass consumption data, particularly for the residential sector, to eliminate discontinuities in per-capita consumption (§2.2.1). This results in a

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fundamental mismatch of biomass drivers leading to unreliable biomass emissions scaling factors. An additional multiplier, which relates the new and old IEA data (before CEDS corrections), is calculated and applied to CEDS emissions, normal EDGAR scaling proceeds, then the reciprocal of the IEA multiplier is applied again to return to normal scaled emissions. This process results in more consistent EDGAR scaling factors, while still retaining the any newer biomass energy revisions.

More details on the scaling methodology and data sources can be found in section 2.4 of Hoesly et al (2018) and its supplement.

2.4.1 Use of satellite and other point source emissions data

Satellite estimates of point source emissions are a valuable adjunct to country inventory data, particularly where high-quality inventory data is lacking. CEDS uses a catalog of SO_2 point sources derived from a multi-satellite dataset (Fioletov et al. 2023a), which is updated annually and extends from 2005 to the present.

Narayan et al. (2023) evaluated an earlier version of this SO_2 catalog against high quality SO_2 emissions data from the United States. They found that the catalog estimates in aggregate, with a number of sources summed together, were unbiased, while at the individual source level uncertainty is larger and consistent biases were sometimes seen. Not all sources are included in the catalog, however, which means that catalog trends are not necessarily representative of overall trends for a sector in any given country. This means that the satellite catalog is particularly useful to provide a lower bound for emissions for large sources, particularly when at least several sources are present for any given sector and country.

Because the point source catalog will include all emissions from within the satellite footprint, we first process catalog emissions by removing our estimates of known point sources, generally power plants. This data is then used in three ways, focusing on the oil, gas, and metal smelting sectors. First, for fugitive oil and gas sector SO_2 emissions, which result from flaring of sulfur rich gases, we use the catalog totals for these sectors as default data for CEDS for countries where we otherwise lack inventory data. We first subtract our *1A1bc_Other-transformation* emissions for that country (refineries and other energy transformation) from the total catalog values and apply the remainder to the *1B2b_Fugitive-NG-distr* and *1B2b_Fugitive-NG-prod* sectors, depending on the source type. This avoids potential double counting.

Significant contributions to SO_2 emissions compared to our default dataset are found, particularly for the Middle East, Mexico, Russia and central Asia. Emissions are extrapolated backwards before the first year of the catalog by using an appropriate driver (refinery throughput, oil or gas production, etc.). The additional natural gas processing SO_2 emissions in Russia obtained in this manner match well the estimates from Ryaboshapko et al (1996).

We also use this data for evaluation of our bottom-up estimates, particularly for non-ferrous metal smelting. Where satellite trends diverge from our bottom-up estimates these country/source combinations are flagged for evaluation using independent data (corporate environmental reports, news stories, etc.). This has allowed us to identify cases where facility upgrades, such as the addition of acid processing plants, subsequently reduced emissions. These cases were documented and the bottom-up estimates adjusted accordingly.

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The final use is to assist in spatially allocating emissions. The spatial locations of emissions supplied in the catalog are used to geolocate all sources that can be identified with a specific CEDS sector. Emissions of co-emitted species are also estimated for each point source for consistency. Earlier historical data for several point sources are also added, for example for the Sudbury and Norilsk smelters, which were likely the largest anthropogenic SO_2 point sources at points over the 20th and 21st centuries.

2.5 Historical Extension to 1750

Historical activity data and emissions factors are extended back to 1750 separately to estimate historical emissions trends. This allows for consistent methods across time and sectors rather than piecing together disparate historical data sets with inconsistent methodologies. In most cases, activity trends drive historical emissions estimates while emissions factors stay constant at their pre-abatement level, however changes in EFs are incorporated where there are known changes overtime.

2.5.1 Pre-1970 Activity Drivers

IEA World Energy Statistics are available back to 1960 for OECD countries and 1971 for non-OECD countries. Energy statistics are predominately extended using historical CDIAC CO_2 emissions, available for aggregate fuels (coal, oil and gas). SPEW data is also used, to match historical total coal use and to transition fuel shares from IEA data in 1960 to SPEW data by 1850, resulting in smoother historical trends for many key countries. Biomass consumption estimates focus on residential consumption, which starts with IEA estimates (adjusted for discontinuities), which are smoothed over time on a rural per-capita basis to match historical estimates from (Fernandes et al. 2007a).

Longer-term historical energy consumption data by broad sector are available for some countries, for example for the USA and the United Kingdom, and these data are used to supplement and extend the IEA data back in time. Note that in these cases, sectoral consumption by sector matches the longer-term country data and may differ from those in IEA in some cases (such as coal consumption in buildings). More details on these methods are given in Section 2.5 of Hoesly et al (2018).

2.5.2 Pre-1970 Emission Factors

While historical trends are largely driven by the activity data – some effort is made to account for changing emission factors through history. Emission factors are extended backward by being keeping constant, converging to a specified value, or extending the emission factor back in time with an emissions or emissions factor trend from a specified data source, such as historical SPEW emission factors, or CDIAC CO_2 emissions.

2.5.3 Pre-1850 CH_4 and N_2O Historical Extension

Methane and N_2O are now extended back to 1750 on a global sectoral level. From 1750 – 1850, methane in agriculture and livestock sectors (3B, 3D, 3E, 3F, and 3I) are extended using the methane extension from CMIP5 agriculture estimates (Lamarque et al. 2010), which was based on HYDE (Klein Goldewijk et al. 2010). N_2O from 3D_Soil-emissions is extended from 1860 – 1960 using historical inferred per capita global N_2O from manure and fertilizer (Davidson 2009). N_2O from 3B_Manure-management are trended from 1800 to 1969 with global nitrogen

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trend estimates (Holland et al. 2005a). While we consider these estimates to be reasonable at a global sectoral level, we did not compile the regional or country level driver data needed to provide robust regional or country estimates.

2.6 Gridded Data

Final aggregate annual emissions estimates are gridded for use in earth system, climate, and atmospheric chemistry models. CEDS emissions are provided at monthly resolution, on a 0.5-degree grid, with 50-years per data file as per ESGF formatting conventions (with 1850 CMIP6 pre-industrial emissions in their own file) in netcdf v4 (HDFv5) format with CF-compliant metadata for nine final gridding sectors. VOC speciation is provided at the 23 species resolution used in HTAP and RETRO. Additionally, downscaled 0.1° grids for recent decades (1980 forward) are available via zenodo (R. Hoesly et al. 2025b).

Annual CEDS emissions are aggregated to 16 intermediate gridding sectors, then spatially distributed using satellite OMI SO_2 point source data (Fioletov et al. 2023b), power plant data (Byers et al. 2018), and global spatial proxies. Spatial proxies are from CAMS (Granier et al. 2019) via the database ECCAD database (Emissions of atmospheric Compounds and Compilation of Ancillary Data - eccad.aeris-data.fr) for shipping, ECLIPSE for flaring, and EDGAR (European Commission, Joint Research Centre (EC-JRC) 2024a, 2024b) for the remaining sectors.

Gridded emissions are aggregated to nine sectors for final distribution: agriculture, energy, industrial, transportation, residential/commercial/other, solvents, waste, international shipping, and aircraft emissions. Details on point source methodologies are available from documentation available on zenodo (Prime et al. 2022a). Emissions are also distributed over 12 months using spatially explicit, sector-specific monthly fractions largely from the ECLIPSE project (Klimont et al. 2017), EDGAR, and Carbon Monitor (Liu et al. 2020). By default, seasonality profiles are assigned depending on sector: ECLIPSE (NH_3 agriculture), CAMS-TEMPO (agriculture, industry, and residential/commercial/other), EDGAR (energy, transport, solvents), and Carbon Monitor (2019–2022 for energy, road transport, and aircraft). A mapping script assigns the appropriate profile to each country, sector, and year, falling back on EDGAR representative years or Carbon Monitor where available. This ensures consistent temporal allocation across sectors while allowing flexibility for user-defined adjustments.

2.7 Supplement and CEDS GitHub.

The above sections give an overview of the main methodology used in CEDS. More general detail is available in Hoesly et. al. (2018) and detail on specific data sources and exceptions can be found in its accompanying supplement. Additional data, assumptions, and methods are all available through the public source data system, released through the CEDS GitHub repository, available at https://github.com/JGCRI/CEDS.

3 Results

3.1 Emissions Trends

Historical emissions trends compared to previous CEDS releases are shown in Figure 1 and Figure 2. The current emissions trends are shown globally by aggregate sector compared to the CMIP6 emission release in the dotted line (CEDS_v_2016_07_26) and the previous CEDS release in the solid line (CEDS_v_2024_07_08). Figure 1 shows comparable figures for historical trends from 1750 – 1965. CH_4 and N_2O are only in aggregate prior to 1970. The

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supplement contains many additional plots of emissions trends by regions and fuels. While emissions estimates from this release at the global level are largely very similar to the previous release (except for historical BC and OC emissions), there are many differences at finer scales, with trends significantly revised since the release of CMIP6 estimates.

From 1750 – 1850, anthropogenic emissions (emissions included in this inventory) are largely dominated by agriculture for NH_3, CH_4, and N_2O emissions and residential heating and cooking for all other emissions species. With the onset of the industrial revolution in the mid 1800's and the rapid increase in industrial fossil fuel consumption, SO_2, NO_X and CO_2 emissions become dominated by industrial sector emissions in North America and Europe. While BC, OC, CO, and NMVOCs see some increase in emissions from industrialization through modern time, these emissions stay dominated globally by residential and commercial sector (RCO) emissions.

From the early 1900's, NO_X and CO emissions from transportation quickly grow with the wide use of motor vehicles. While CO continues to have a large portion of RCO emissions, by the 1970's transport and RCO emissions are roughly equal, then transport emissions swiftly decline with the introduction of the catalytic converter. NO_X emissions continue growing until peaking and decreasing around 2010, largely due to international shipping and energy transformation.

SO_2 emissions continue to grow through the 1970's, dominated by energy transformation and industrial sectors, then slowly decline with the wide introduction of sulfur control measures. Globally SO_2 emissions from the industrial sector begin declining in the 1970's, from the residential sector in 1990, and from the energy transformation sector in the mid 2000's. Globally, while SO_2 flattens and declines from the 1970's, regional SO_2 trends vary wildly. SO_2 from North America and Europe decline rapidly from the late 1970's and early 80's but steadily continue to rise in China, Africa, and South America. SO_2 in China rapidly increases in the early 2000's until its peak and rapid decline in the mid 2000's, continuing through the late 2010's.

Similarly, while North America and China NO_X emissions steadily decline from the 1970's and 80's, NO_X emissions in China steeply rise from 2000 through the 2010's then decline, while NO_X emissions in Africa, South America, and the Middle East steadily increase then flatten in the late 2010's.

BC and OC emissions estimates are significantly smaller from 2000 onward in CEDS inventories since CMIP6 estimates, reflecting an improved representation of residential biomass and an improved representation of BC from coke production in China drawing from Xu et al. (2019) and the LBNL China Energy Databook (Zhou et al. 2022) with emission factor controls after 2012 following GAINS (Klimont et al. 2017). Overall, compared to the most recent CEDS release, BC and OC emissions before 1950 are 10-20% higher, predominately because of larger emission estimates from biomass in North America.

Globally NH_3 and N_2O grow steadily from the mid 1900's through recent times. However, NMVOC emissions in North America begin declining in the 1970's and in Europe flatten then decline in the 1970's and 1990's. NMVOC's steadily increase in China and Africa, South America, and Middle East. Global NMVOC emissions estimates from the 1970's moving forward have decreased from CMIP6 estimates by 10 – 20 Mt.

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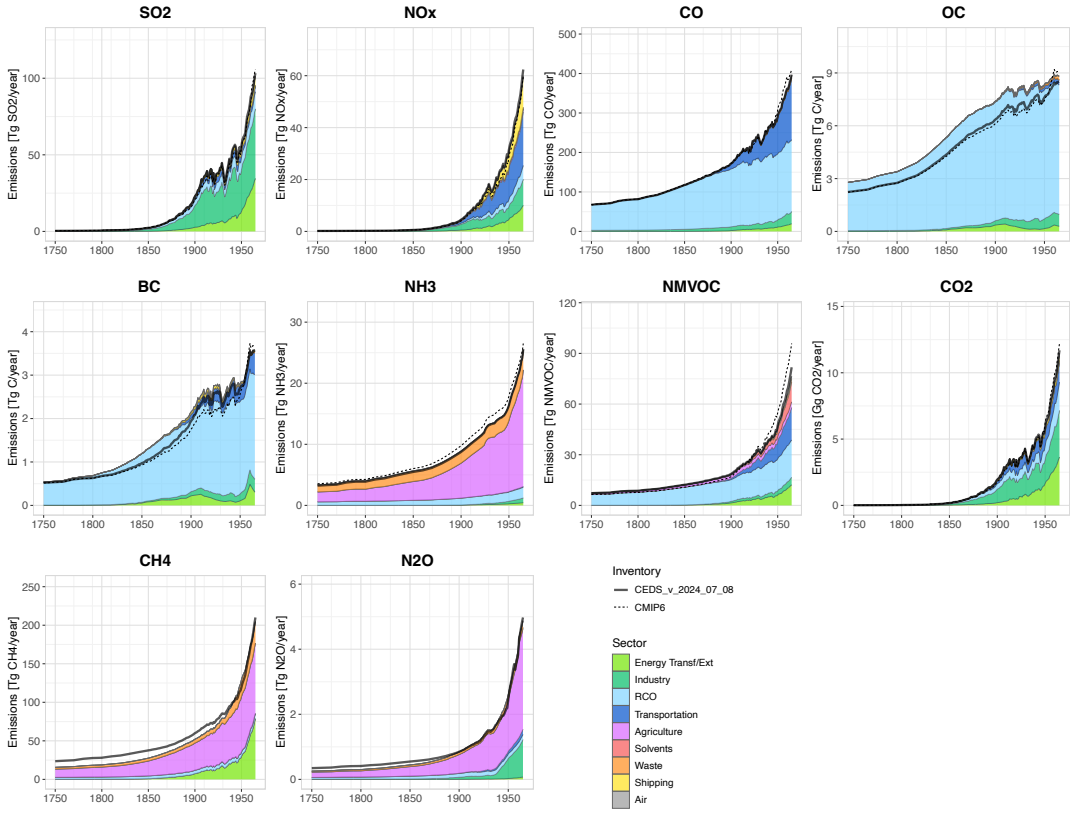
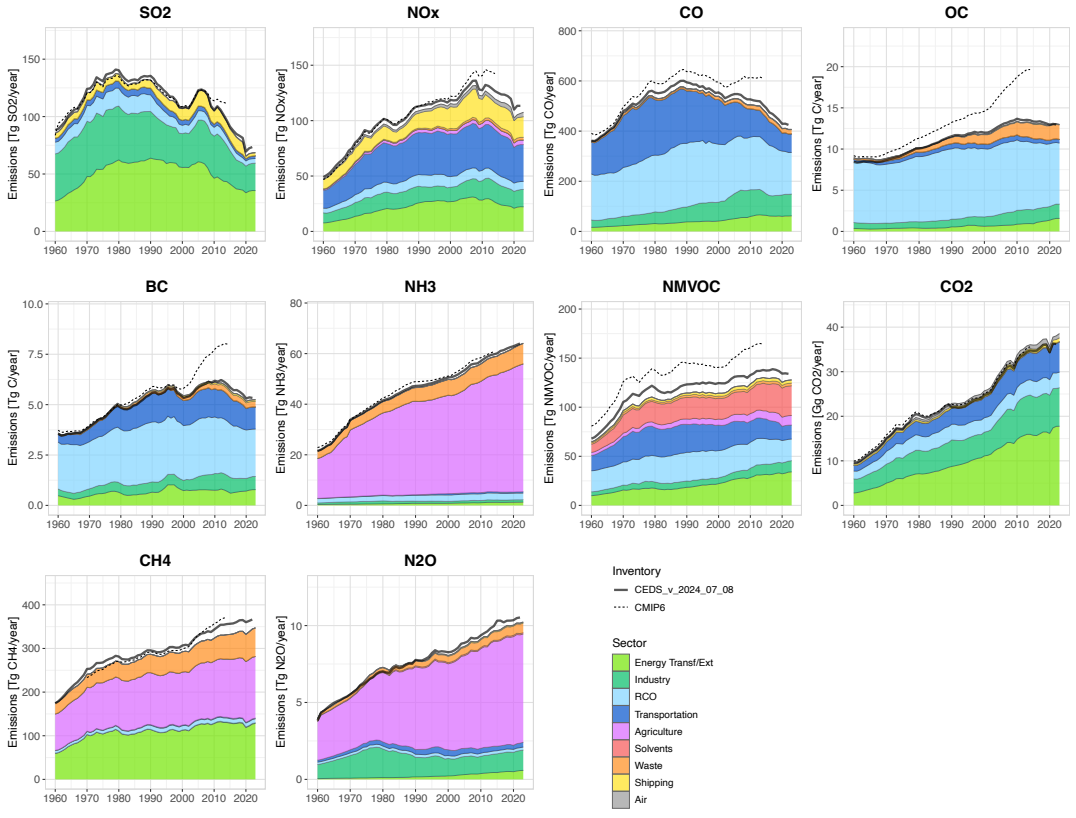


Figure 1: CEDS emission estimates from 1750 – 1965 by aggregate sector compared to the previous CEDS release (CEDS_v_2024_07_08) and CMIP6 (CEDS_v_2016_07_26). These figures do not agricultural waste burning on fields. "RCO" stands for residential, commercial, and other. Supplementary CH_4 emissions were extended back to 1850 for CMIP6. N_2O emissions were not estimated for CMIP6.

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360 **Figure 2: CEDS emission estimates from 1960 – 2023 by aggregate sector compared to the previous CEDS release (CEDS_v_2024_07_08 shown in the solid line) and CMIP6 (CEDS_v_2016_07_26 shown in the dotted line). These figures do not include agricultural waste burning on fields as these emissions are not estimated by CEDS. "RCO" stands for residential, commercial, and other. N_2O Emissions were not estimated for CMIP6.**

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3.2 Emissions Trends in Recent Years (2010 – 2023)

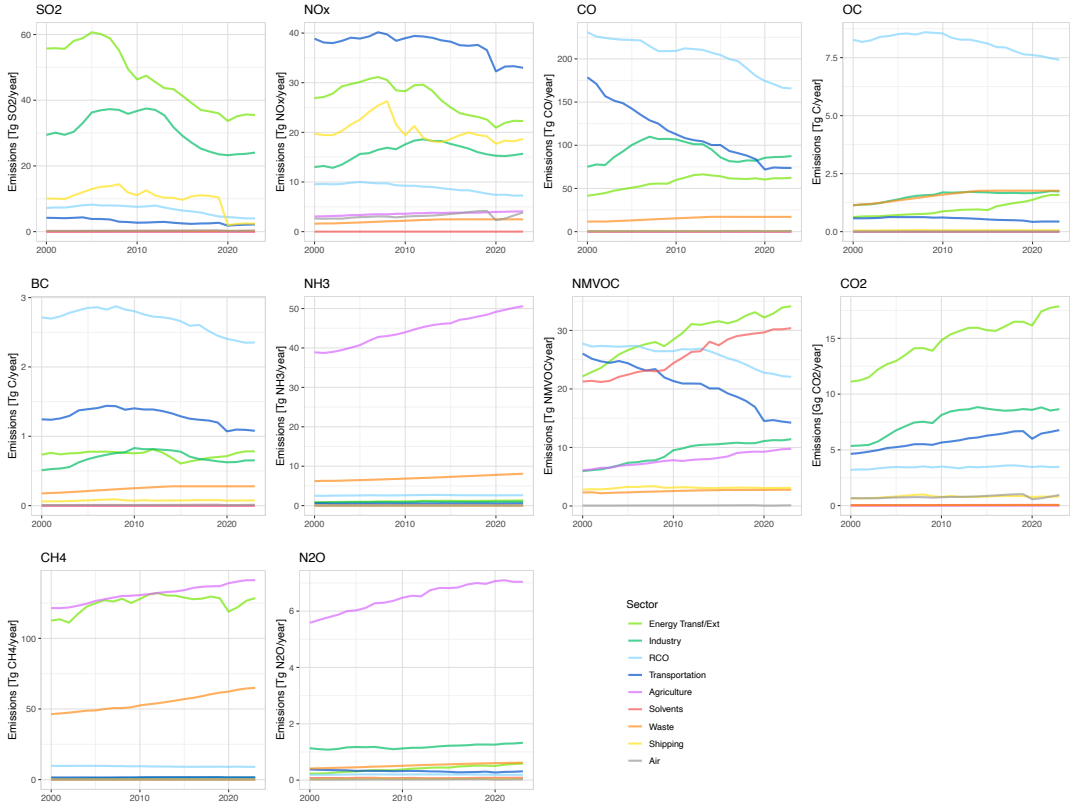


Figure 3: CEDS emission estimates from 2000 – 2023 by aggregate sector. These figures do not include agricultural waste burning on fields as these emissions are not estimated by CEDS. "RCO" stands for residential, commercial, and other.

In the years since 2010, SO_2, CO, NO_X, and BC decline, while NH_3, CH_4, CO_2 continue to rise at varying rates. NMVOC has stayed relatively flat in the past 2 decades. Many emissions species (excluding, NH_3 and OC) show clear dips in 2020 due to COVID-19, but have since rebounded, some rebounding to their previous rate of increase (CO_2 and CH_4) and others flattening (BC, NO_X, CO, and NMVOC).

Global SO_2 emissions peak then decline in the mid 2000's, continuing to decline until a major dip in 2020 then flattening through 2023. Global decline in SO_2 emissions come from emissions mitigation predominately in energy transformation and industrial sectors in China, with significant decrease in 2020 from international shipping, which flatten, rather than rebound through 2023. While CMIP6 emissions trend estimates global industrial emissions slowly growing from 2005 onward, updated CEDS estimates industrial SO_2 emissions flattening through 2017 then declining. The 2020 dip in SO_2 emissions is primarily due to COVID and the introduction of new emission controls standards in shipping.

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Similarly, emissions mitigation efforts in China result in declining emissions for CO, NO_X, and BC, while other regions see modest increases or flattening trends since 2010. Conversely, while CO_2 emissions in most regions have flattened or decreased since 2010, CO_2 emissions continue to steadily climb in China since the early 2000s, dominated globally by steadily growing emissions from energy transformation sector, and modestly growing emissions from the transportation sector.

3.3 Highlighted Changes in Emissions compared to CMIP6

The most significant revision in emission trend since CMIP6 are industry and energy transformation BC emissions in China in recent decades. Changes in BC emissions are largely due to scaling to more updated and available inventories, since CMIP6 era data. CMIP6 estimates showed BC emissions rapidly increasing from 2000 then leveling off by 2014 (the last year of CMIP6 data), but updated emissions trends estimate a more modest increase in BC emissions from 2000, leveling off by 2012, followed by a steady decrease through 2020. Current BC emissions estimates for Africa and Other Asia have also reduced from 1960 onward due to revisions in residential biomass estimates while BC emissions in North America (transport and RCO) over the same period are larger than CMIP6 estimates due to updated BC and OC scaling with country inventories.

Global NMVOC emissions have reduced by about 20% compared to CMIP6 estimates largely due to decreases in Africa and Other Asia in energy transformation and transportation sectors. CO emissions estimates have globally reduced about 10%. However, this is net change across various increases and decreases in different regions. CO emissions increased about 25% in China, largely in industry and RCO, but decreased by about a third in Other Asia in RCO, industry and transportation. OC emissions have also globally decreased in recent years, mostly due to biomass data revisions, updated waste estimates, and energy transformation corrections in China (Li et al. 2023). Revisions in other emissions species remain more modest, globally balancing across trends with larger revisions in recent year trends in the last decade, as is common with emission updates as the most recent years are the most uncertain estimates.

A full set of detailed figures comparing this CEDS release and CMIP6 CEDS release by aggregate sector, fuel, region, and for select countries are available in the supplement.

3.4 Highlighted Changes in Emissions compared to previous CEDS releases

While updates to energy data often result in revisions of biomass use, especially in the building sector in developing areas such as Africa and Asia, where residential biomass use is significant and not well accounted for – this update also includes revisions to historical residential biomass use in North America, resulting in significant increase (about 20%) in historical residential BC emissions from the 1950's through the mid 20th century. This version of CEDS also includes updated BC and OC scaling via EDGAR for USA, Canada, and larger European and Asian countries for road and building emissions. Additionally, BC and OC historical emission factor extension was adjusted to increase low BC and OC emission factors to match premodern SPEW values particularly in North America and Europe. BC and OC emissions from coke production in China were revised to better track results from Xu et al. (2019).

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Global waste methane emission defaults have been reduced after 1960. This leads to reductions in waste emissions (sometimes up to about 20%) in areas without significant inventory scaling such as Latin America and Other Asia, while North American methane waste emissions have not changed. Other major methane revisions include historical emissions from agriculture in Europe, China, North America, and the Former Soviet Union and reduction in energy transformation methane emissions in the mid-century in Former Soviet Union.

Other changes include: CO reduction in the late 20th century and recent decades are seen in Other Asia and the Former Soviet Union, primarily in transportation, buildings and energy transformation; increased NH_3 emissions from agriculture in the Former Soviet Union since 2010; a global decrease in NMVOC since 1970 primarily from Other Asia in energy transformation, industry and solvents; and decrease in NO_X emission in Other Asia in the modern era across transportation, industry, and energy transformation. A full set of figures comparing this CEDS release and the previous CEDS release (CEDS_v_2024_07_08) by aggregate sector, fuel, region are available in the supplement.

3.5 Gridded Emissions

Figure 4 shows the difference in total emissions between this version of CEDS and the CMIP6 emissions for SO_2 in 2000 at 10-degree grid. Since the CMIP6 data release, significant methodology improvements have been implemented, particularly the inclusion of point source data in the gridding process, which was first incorporated and documented in a special release of CEDS_ v_2021_04_21 (Prime et al. 2022b). This new methodology corrected the notable CMIP6 east-west distribution error of SO_2 in the US, as seen in Figure 4.

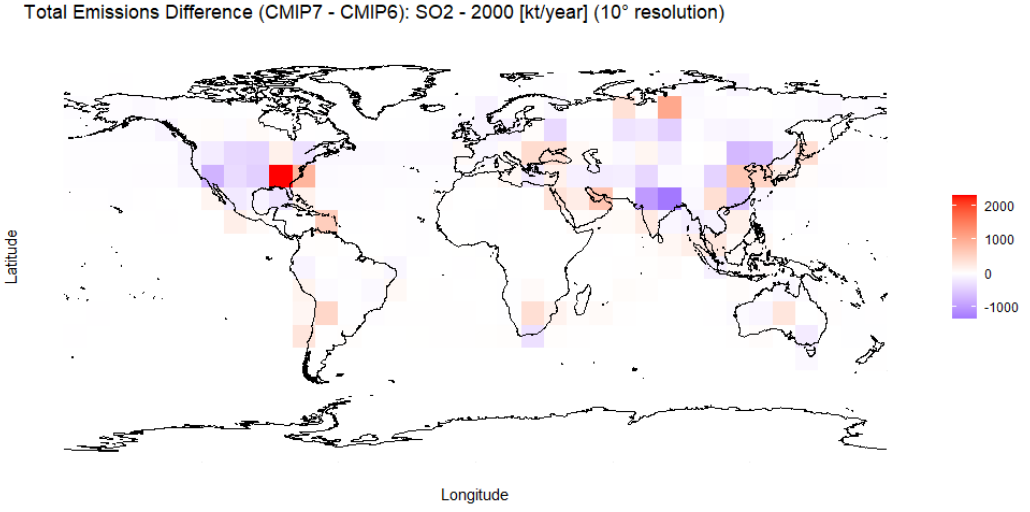


Figure 4: CEDS gridded SO_2 emissions (aggregated to 10 degrees) comparison between CMIP6 and CMIP7. Positive values in red show in an increase from CMIP6 to CMIP7. Negative values, shown in purple, indicate a decrease from CMIP6 to CMIP7. Differences can arise from both differences in the underlying estimate by country-sector and differences in the spatial allocation of emissions within a country.

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Other similar figures for all emission species at various years comparing this version of CEDS to both CMIP6 estimates and the previous the CEDS release (CEDS_v_2024_07_08) are included in the supplement. Most differences in gridded data distribution between this release and the previous CEDS release (i.e. changes not attributable to the update and revision of aggregate annual emissions estimates) can be attributed to updates in the underlying gridding proxy data from EDGAR, and the inclusion of new data sets to determine seasonality by sector, detailed in section 2.6.

4 Comparison with Other Inventories

Figure 5 shows global comparison for select emissions species across CEDS, EDGAR, HTAP, and GAINS. These figures show a like with like comparison, excluding biomass burning, aviation, and shipping. While most inventories have a good agreement in recent years for most emissions species, historical trends become more divergent going back in time for BC, OC, and CO. For BC and OC, CEDS uses a more independent method for developing estimates, rather than relying on predominantly EDGAR or GAINS as is the case for many other species. Additionally, BC and OC emissions are less frequency scaled to other inventories – often scaling only occurs for road emissions. For CO, CEDS had good agreement with EDGAR-HTAP, as CEDS often has very good agreement with EDGAR-HTAP because both these inventories rely heavily on official regional and national inventories, while EDGAR and GAINS provide more independent estimates. EDGAR estimates lower global BC emissions than the other inventories, which is apparent across many regions including Europe, Africa, Asia and the Middle East (shown in the supplement).

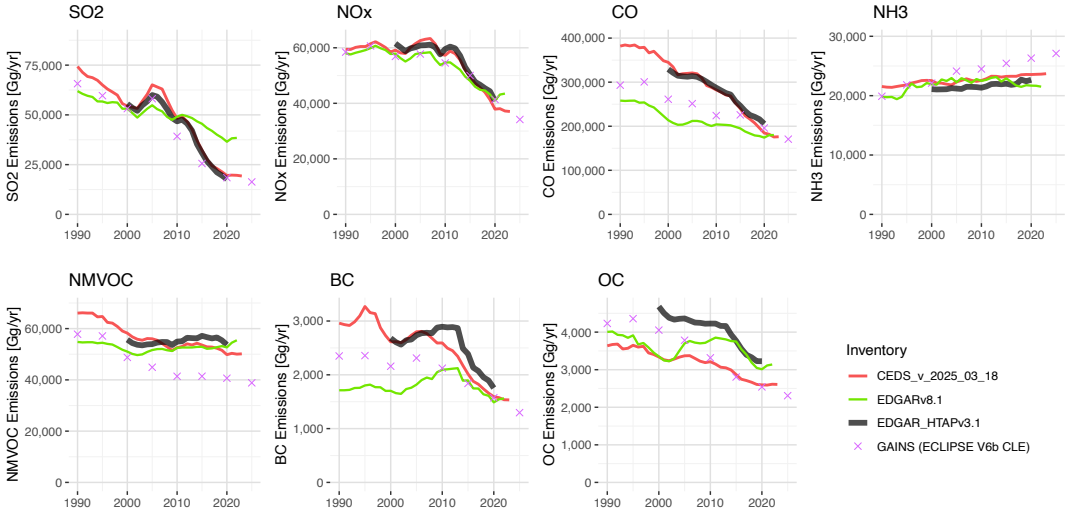


Figure 5: CEDS global air pollutant emissions compared to EDGARv8.1, EDGAR-HTAPv3.1, and GAINS.

Figure 6 shows SO_2 compared over the same inventories as well as national inventories and REAS, a regional Asian inventory. EDGAR has higher global estimates for SO_2 than the other inventories in recent years, largely due to estimates in China, shown in Figure 6. While CEDS, GAINS, and the regional inventories estimate significant drops

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in SO_2 from 2010 – 2023, EDGAR estimates a much more modest decrease, about 25,000 Gg in 2020 compared to 10,000 Gg.

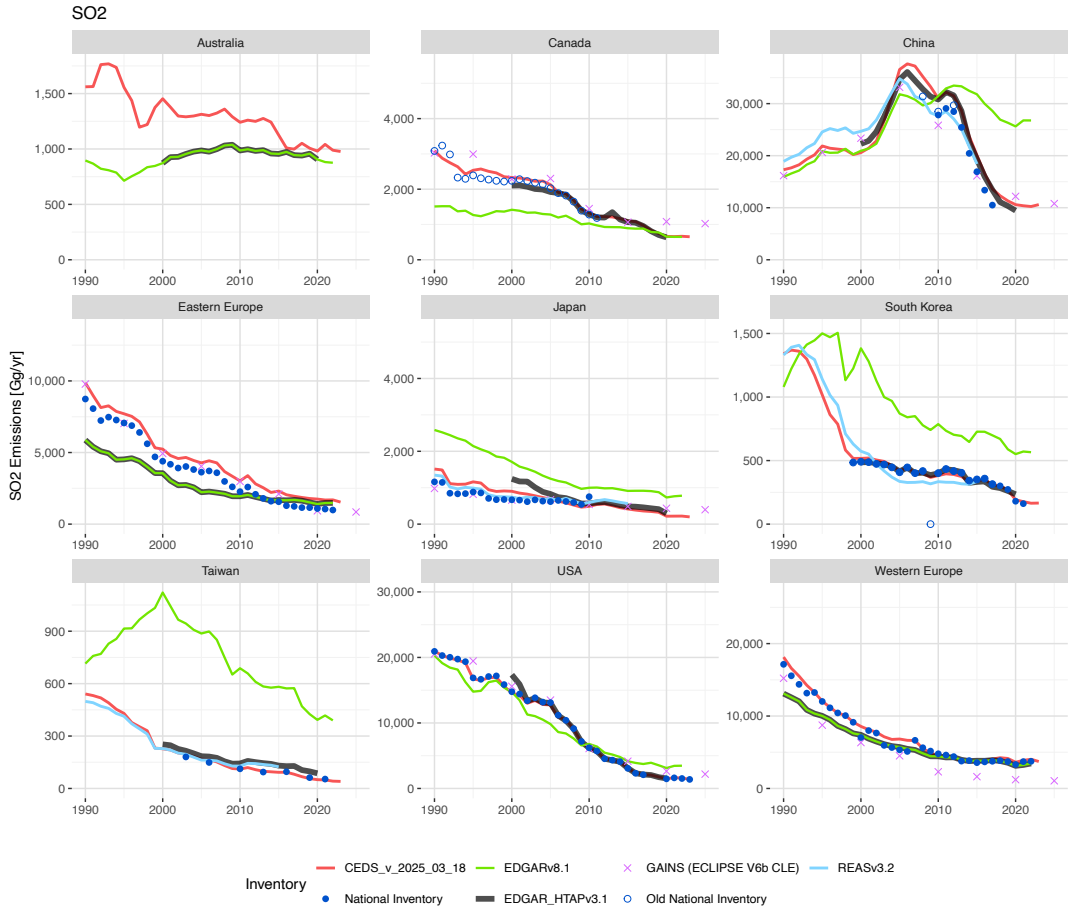


Figure 6: CEDS SO_2 emissions compared to other inventories for select countries/regions.

A full set of figures for all relevant emission species comparing CEDS to other inventories by region, select countries, and globally is available in the supplement. Globally, CEDS OC estimates tend to be lower than other inventories, sometimes by up to 1000 Gg, mostly following EDGAR before the mid 2000's when EDGAR estimates increase in China, while other inventories flatten or decrease. Through the most recent estimates, global CEDS OC emissions continue to decline alongside GAINS estimates. CEDS OC estimates for the US are larger than EDGAR and GAINS, and slightly larger than HTAP by about 500 Gg. Unlike other emissions estimates (NO_X, CO, NH_3 , and NMVOC) CEDS estimates for OC and BC are largely independent from the other inventories in this comparison and yield larger differences. Globally NO_X, NMVOC, NH3 emissions are more similar across inventories, usually with CEDS, HTAP, and EDGAR all within around10%. Globally CO emissions estimates across inventories have converged in recent years, spanning differences of about 25% in 1990, but with small differences in recent years.

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The range of global BC emissions estimates have also decreased in recent years, where EDGAR and CEDS differed by almost 40% in 1990, but only span about 15% in 2020, largely due to historical estimates in China.

CEDS emission totals may differ from other inventories, most often because of mismatches in sector representation. For example, CEDS does not include agricultural waste burning, prescribed burns, or dust, which is often included in national inventories, but does include NOx from agricultural fields, which are sometimes not included, or differences in how bunker fuels are reported.

While CEDS often aims to match national inventories in a like with like comparison, it's sometimes not possible due to differences in sector definitions or fundamental differences in underlying assumptions or energy, as is often the case with off-road emissions. Some notable instances where CEDS emissions do not align with national inventories include Japan NOx (CEDS is smaller by about 25%), Canada VOC (CEDS is smaller by 15% in 2010), NH3 in USA (CEDS is smaller by less than 10%), and NH3 in western Europe (CEDS is larger by about 10%).

5 CEDS forcing data in a Simple Earth System Model

CEDS forcing data described here was used in a simple Earth System Model, Hector v3.2 (Dorheim et al. 2024), along with the CMIP6 anthropogenic forcing data set for comparison to see how forcing changes across the data sets. Hector is an open-source, reduced-complexity model of the Earth System. It uses highly parameterized, simplified equations to represent the major carbon cycle, ocean, and atmospheric dynamics on a global scale on an annual basis. This includes exogenously defined inputs for 37 different emission species. Annual CO_2 emissions and land, atmosphere, and ocean carbon fluxes computed by Hector drive changes in atmospheric CO_2 concentrations. The CO_2 concentrations, non-CO_2 radiatively active atmospheric gas concentrations, aerosol and other pollutants alter Hector's energy balance and global temperature (Hartin et al. 2015; Dorheim et al. 2024). Default simulations in Hector use emissions data from the RCMIP protocol (Nicholls et al. 2020) which incorporates the CMIP6 CEDS emissions for the historical period, along with harmonized shared socio economic pathway (SSP) emissions (Gidden et al. 2019) for future projections. Default simulations were compared here with simulations replacing CEDS CMIP6 emissions with this CEDS release for BC, CH_4, CO, CO_2 from fossil fuels and industry, N_2O, NH_3, NMVOCs, NO_X, OC, and SO_2. CMIP6 historical emissions were extended to 2023 using future emissions from SSP2-45 for the years 2015 to 2023 for comparison to CMIP7 data. CEDS CMIP7 data was supplemented using CMIP6-era open burning emissions, for direct comparison.

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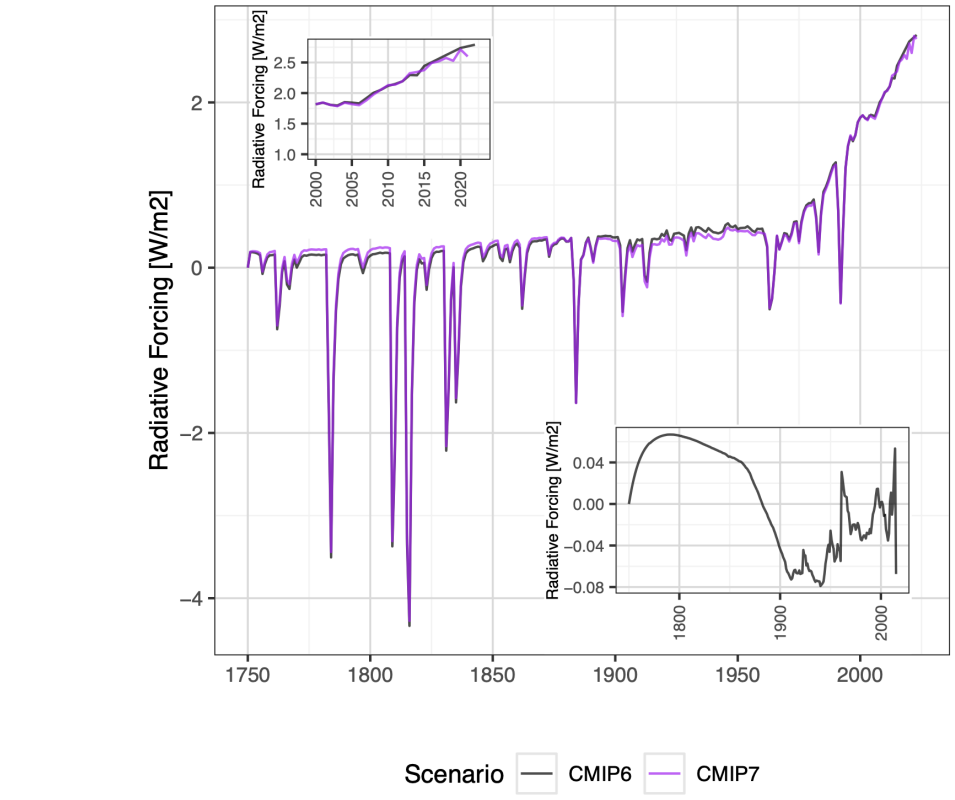


Figure 7: Total Radiative Forcing from CMIP6 and CMIP7 emissions. Figure inserts show the difference in radiative forcing between datasets (bottom right) and forcing for both data sets in recent years (top left).

Total radiative forcing from CMIP6 and CMIP7 emissions data sets are shown in Figure 7 (main figure). From 1750 through the mid 1900s, CMIP7 emissions yield slightly larger total radiative forcing, however, from the mid 1800's through the mid 20th century, CMIP7 forcing is lower, by up to 0.08 W/m^2, shown in the bottom right. From the end of the 20th century through the most recent years, CMIP7 data still yields mostly smaller total forcing than CMIP6 data. From 2015 forward, CMIP7 data shows expected noise from interannual variability and observed emissions of real data, especially in 2020, while the CMIP6 comparison is from smooth projected scenarios that are yield more radiative forcing than actual data from recent years. Additional results of this analysis, including the radiative forcing from each emission species, are in shown in the supplement.

6 Uncertainty

Emission inventory estimates are uncertain, with the level of uncertainty depending on the emission species, sector, year, and quality of the source data. While uncertainty has not yet been formally quantified for the CEDS data, we provide a general discussion of relative uncertainty.

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Uncertainty tends to systematically vary depending on the emission processes involved. Processes that are often highly uncertain include fugitive emissions, incomplete combustion, and biological processes. The lowest uncertainty occurs in combustion processes where oxidation is nearly complete. Most of the carbon in fossil fuels, for example, is converted to carbon dioxide during combustion, resulting in low uncertainty for CO_2 emissions where high-quality fossil fuel consumption statistics are available. Sulfur-containing compounds also readily combust, forming sulfur dioxide (and higher oxides), resulting in relatively low uncertainty where good data on the sulfur content of fuels and feedstocks are available.

Emissions that result from incomplete combustion, such as BC, OC, CO and NMVOCs, also tend to be highly uncertain. This is because emission factors depend on details of actual combustion processes and conditions, which are often difficult to measure. Figure 8 shows the implied emission factor in the CEDS data for CO emissions from light oil (e.g. gasoline) in the road vehicle sector. These implied emission factors are the result of CEDS scaling to country-level emission inventories for countries where both the inventory and fuel consumption data were judged to be of high quality. CO emission factors vary over a factor of 1.75 and 1.68 (relative to median) in 1990 and 2023 respectively. We note that the implied emission factors are not converging to a common value in earlier years, although in all these countries emission factors have decreased substantially over time as emission standards have lowered and engine efficiency has increased. The open question regarding uncertainty is: to what extent does this represent a true (real world) divergence in the combination of engine emission properties and vehicle use patters as contrasted to differences in inventory assumptions? The answer is likely a bit of both, with a substantial uncertainty in the inventory results. Note that one, often large, element of uncertainty in such cases is the extent to which the inventory methods can accurately account for divergences between data generated during testing conditions, which is often the basis of inventory calculations, and real-world behavior and conditions.

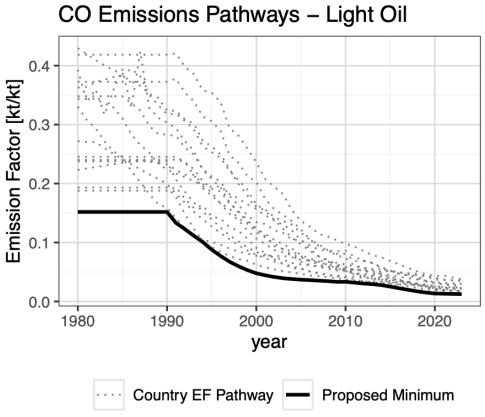


Figure 8: Implied CO emission factors (see text) for gasoline combustion in road vehicles for a sample of countries judged to have high-quality data. The implied emission factor is obtained during the CEDS scaling operation where default emissions are scaled to match, by sector, inventory values.

BC and OC emissions, which primarily are from combustion processes, are particularly uncertain. This is because emission factors can vary over several orders of magnitude depending on both combustion conditions and emission

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control devices (Klimont et al. 2017), BC/OC emissions are often estimated by starting with an emission factor for overall particulates (often PM2.5, emission of primary particles less 2.5 μm) then applying speciation fractions indicating how much of the PM2.5 is BC vs OM (organic matter), with further assumptions for the carbon fraction of organic matter. This speciation step introduces additional uncertainty, particularly when speciation profiles are applied at a sector, and not technology, level. Both PM2.5 emissions and BC and OC fractions are very sensitive to combustion conditions. Emission controls or technology change can also have a large impact on these parameters.

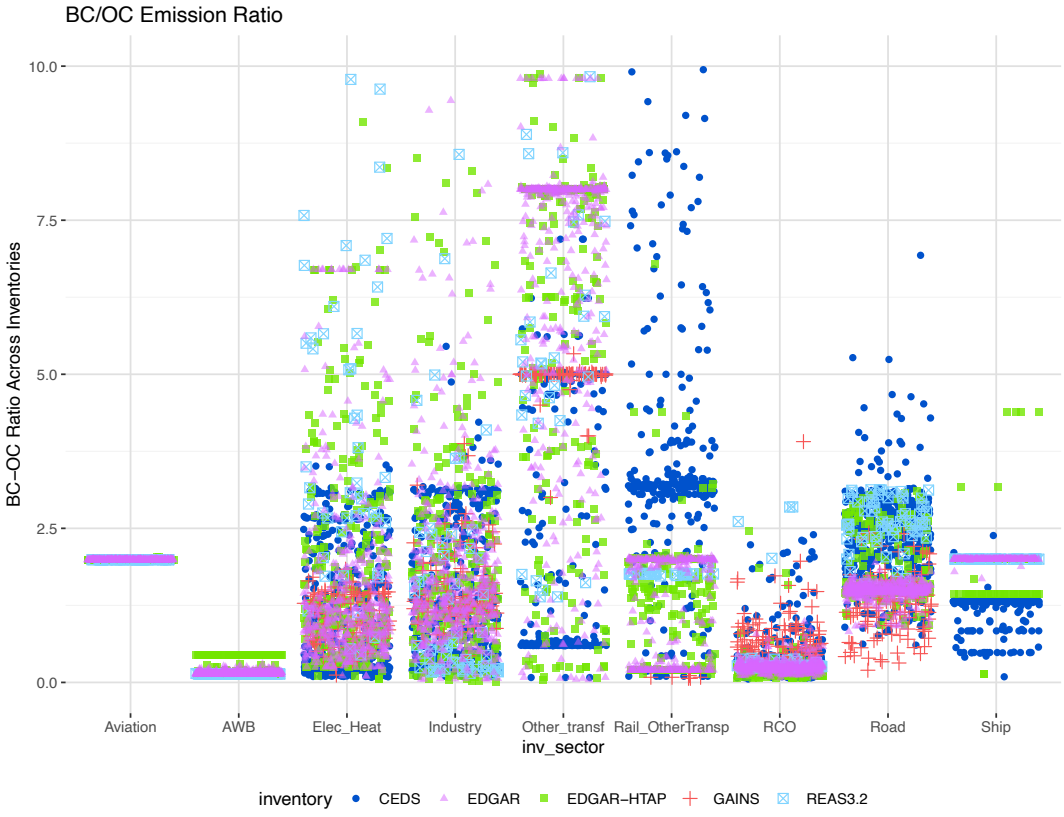


Figure 9: BC/OC emissions rations by aggregate sector across various inventories. Horizontal features in the graph indicate common assumptions for some group of countries within a specific inventory.

The ratio of BC to OC emissions can vary substantially between sectors and across inventories, as seen in Figure 9, which shows ratios of BC and OC emissions across 5 inventories: CEDS, EDGAR, EDGAR-HTAP, GAINS, and REAS3.2. CEDS default BC/OC emission assumptions are largely derive from Bond et al. (2007). CEDS assumptions range across the spread of other inventories, although some assumptions are higher than other inventories (comparable to the BC/OC ratio in the US 2021 NEI for off-road diesel equipment) (US EPA 2021), indicating a potential need for revised assumptions for some countries. In some cases, there is only one or two common assumptions for a given sector, which should not be taken as limited uncertainty in that case. We note also

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that some sectors, such as other transformation, are very diverse and results could be impacted by particularly high or low emissions in a specific sub-sector.

A final step in estimating uncertainty is combining uncertainties across sectors and regions. This step is highly sensitive to assumptions regarding statistical independence. In reality, estimates are rarely fully statistically independent, with some common underlying assumptions used across sectors or regions and with correlations between activity data also present. Even a relatively small amount of correlation across categories or regions can substantially increase total uncertainty as compared to an assumption of complete statistical independence.

7 Limitations and future work

While CEDS produces a unique, long-term data set that prioritizes consistency in trends overtime, it is not an entirely independent inventory and is heavily dependent on existing data, especially EDGAR, GAINS, and many country-level inventories. As such it should not treated as an independent estimate, for most emission species, in meta-analyses and comparison studies.

The primary focus of CEDS is air pollutant emissions and some GHG emissions (CO_2, N_2O, and CH_4) have been added at the request of the modeling community to provide self-consistent estimates to be used alongside air pollutant emissions. The historical extension from 1960/1970 back to 1750 for the main emissions species are much more robust than the N_2O and CH_4 extensions. Regular extension methodology includes extending activity and emission factor data back separately, with country specific data when available. However, N_2O and CH_4 extensions are reliant on older emissions estimates (CMIP5) with aggregate regional resolution, rather than detailed country specific historical trends of relevant proxy data. These estimates are reasonable at high-level geographies and aggregate sectors, but less reliable at more detailed levels. While these supplementary extensions are provided with the regular data, they should not be considered as robust as the primary historical extensions for other emission species.

CEDS is a long-term, ongoing project that is continually updated and improved. Development in the near future will focus on improving the spatial allocation of emissions data and increasing detail of the energy transformation sector estimates. CEDS currently uses a somewhat inflexible gridding technique that requires global spatial proxies. It will be useful to expand these methodologies to more flexibly use regional spatial proxies, incorporating data from high quality spatially resolved datasets. CEDS will also continue to incorporate satellite data where available and appropriate to better resolved spatial allocation of emissions.

As with most air pollutant inventories, there is substantial uncertainty that is difficult to quantify. More systematic comparisons between observationally-derived emission estimates using multiple methodologies and bottom-up inventories will be critical to improving emission inventory accuracy.

8 Conclusions

CEDS emissions estimates utilize existing energy, emissions, emission factors, and other indicator data sets to develop transparent, consistent, long-term estimates of aerosols, aerosol and ozone precursor compounds, and select GHG's. CEDS combines existing data with consistent and novel methodologies – smoothing discontinuities over

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separate components of hundreds of highly detailed and inconsistent datasets. While CEDS relies heavily on foundational data sets (i.e. EDGAR and GAINS), along with hundreds of other data sets, CEDS is different from these inventories. CEDS can quickly incorporate new data at varying resolutions, while maintaining detail over long time horizons, which is not the focus of these other inventories.

CEDS doesn't reduce the need to more detailed inventories. While the detail of CEDS aggregate emission estimates is often more refined than national inventories, releasing estimates at a detailed fuel and sector level, it is too aggregate for analysis related to specific technologies. For example, CEDS estimates aggregate road emissions would not be refined enough for analysis related to vehicle turnover rates.

CEDS is an open-source community project and the CEDS team welcomes comments, feedback, and collaboration via the CEDS GitHub. The data system supporting this work uses many additional data sources documented on the GitHub site including data and assumptions from the following published journal articles:

(Zheng et al. 2018; Kurokawa et al. 2013; Etemad et al. 1991; Pfeiffer et al. 2019; Eyring et al. 2010; Yevich and Logan 2003; Fernandes et al. 2007b; Wiedinmyer et al. 2014; Behrendt et al. 2025; Hua et al. 2016; Denier van der Gon et al. 2015; Holland et al. 2005b; Gajbhiye et al. 2023; Lee et al. 2010; Srirattana and Piaowan 2020; Punyawadee et al. 2008; Smith et al. 2011)

9 Data Availability

Aggregate annual emissions data, CEDS v_2025_03_18, documented and available via Zenodo: https://doi.org/10.5281/zenodo.15059443 (R. Hoesly et al. 2025a)

Including:

CEDS_v_2025_03_18_aggregate.zip (estimates by sector, by country, by fuel, by country and fuel, by country and sector, and by sector and fuel)

CEDS_v_2025_03_18_detailed.zip (estimates by country, sector, and fuel)

CEDS_v_2025_03_18_supplementary_bunkers.zip (Additional detail for aviation and shipping by country)

CEDS_v_2025_03_18_supplementary_extension.zip (Extended global time series for CH_4 and N_2O)

Gridded 0.5-degree gridded data and gridded 0.1 gridded data, CEDS v_2025_04_18, for recent years available for download via ESGF and documented here: https://doi.org/10.5281/zenodo.15127477 (R. Hoesly et al. 2025b)

Downscaled 0.1-degree gridded data for recent years available for download via ESGF and documented here: https://doi.org/10.5281/zenodo.15001546 (R. Hoesly et al. 2025c)

Supplement

Supplement files related to this article are in one zipped file including a read me (pdf), a pdf of supplementary text, and folders with supplementary figures.

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Author Contributions

Paper preparations: RMH and SJS

CEDS development: RMH, SJS, HA, NP, PO, LF

Emissions Analysis: RH and SJS

Hector Analysis: KD, RH

Data contribution: MC, ZK, DG, CH, BM, SW

Competing Interests

The authors declare that they have no conflict of interest.

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