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A near-real-time monthly dataset of CO_2, CH_4, and N_2O emissions from fossil fuel combustion

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Abstract. Fuel-combustion greenhouse gas emissions account for about 67% of the total anthropogenic emissions, and thus reliable estimates lay the foundation for the Global Stocktake, the evaluation of nationally determined contributions (NDCs), and the quantification of remaining carbon budgets. However, to fully understand the current status of greenhouse gas emissions and to formulate policies for effective control of greenhouse gas emissions, a dataset that provides a comprehensive, up-to-date, and sector-specific record of greenhouse gases is needed. This paper presents a global dataset covering CO_2, CH_4, and N_2O from 1960 to 2025. The dataset reports emissions classified by country, sector, fuel, and gas at monthly resolution, covering emissions from fuel combustion. It covers 153 reporting entities, which consist of 150 individually reported countries, one residual entity covering 48 remaining countries and territories, international aviation, and international shipping. Historical emissions from 1960–2023 are reconstructed using emission factors and statistical data of energy consumption derived from International Energy Agency (IEA) energy activity dataset. For the latest two years without available IEA activity data, we constructed a framework for predicting emissions based on historical emissions data and monthly activity indicators from CEIC. We evaluate six individual prediction methods and their ensembles using historical emissions from 2019 to 2023 and select the best prediction method for each specific country, sector, and gas combination. The best method is applied to estimate annual emissions for 2024–2025. In addition, we distribute the annual emission values to monthly values by using monthly activity patterns. The dataset demonstrates that CO_2 and N_2O show overall increasing trends with CO_2 reaching 37.7 Gt CO_2 yr^{-1} in 2025 and N_2O reaching 1,057 kt N_2O yr^{-1} in 2025. In contrast, CH_4 reached its peak around 1990 and then declined and remained close to 11 Mt CH_4 yr^{-1}. Emissions of all three gases also follow a seasonal pattern with emissions being highest in winter and lowest in summer. For validation purposes, we compare our dataset with existing datasets and find good overall agreement. This dataset supports carbon budget tracking, NDC and Global Stocktake assessment, and near-real-time monitoring of sectoral greenhouse gas emissions.

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1 Introduction

The combustion of fossil fuels for electricity, heat, transportation, and industrial processes is responsible for about 67% of all global greenhouse gas emissions (Ritchie, 2020). Carbon dioxide (CO_2) emissions from coal, oil, and natural gas dominate this total, but the same activities also emit substantial amounts of methane (CH_4) and nitrous oxide (N_2O). CH_4 is especially concerning because it has nearly 30 times the warming potential of CO_2 over a 100-year horizon (Forster et al., 2021), making it a critical target for short-term climate action. N_2O, though less discussed, is a long-lived gas with 273 times the warming potential of CO_2 over a 100-year horizon, and it is produced by fuel combustion in vehicles and power plants (Forster et al., 2021). Because the energy sector is both the main problem and the main opportunity, tracking its emissions accurately and promptly is not a niche scientific task, but a foundation for any realistic plan to mitigate climate warming (Forster et al., 2025; Lamb et al., 2021).

To monitor energy-related emissions, the world currently relies on two broad types of datasets, each with serious limitations. The first category includes databases such as the Emissions Database for Global Atmospheric Research (EDGAR) (Crippa et al., 2024) that provide long-term estimates of CO_2, CH_4, and N_2O for many countries and sectors. The Global Carbon Budget (GCB) and the Carbon Dioxide Information Analysis Center (CDIAC) give global and national fossil CO_2 records that also support carbon budget assessment, while PRIMAP-hist reports national time series for the Kyoto greenhouse gases which include CO_2, CH_4, N_2O, and some other gases such as hydrofluorocarbons (Friedlingstein et al., 2026; Gilfillan and Marland, 2021; Gütschow et al., 2016). Countries also report their own emissions through national inventories submitted to the United Nations Framework Convention on Climate Change (UNFCCC) (Banja et al., 2025). These datasets are built on official energy statistics collected from national agencies, giving them a strong factual grounding. However, the process of gathering, checking, and compiling these statistics introduces substantial delays. To reduce this delay, EDGAR extrapolates emissions for the latest years using growth rates from the Energy Institute and allocates them to sectors according to the latest sectoral structure available from the IEA (Guizzardi et al., 2025; Crippa et al., 2025). As a result, recent changes in individual sectors may not be fully captured, and the relatively late annual release limits its usefulness for timely policy assessment. The second category focuses on near-real-time updates. Carbon Monitor estimates CO_2 emissions using rapidly updated activity data, including electricity generation, industrial production, traffic, aviation, and shipping activity (Liu et al., 2020; Dou et al., 2022; Li et al., 2026). The Open-source Data Inventory for Anthropogenic CO_2 (ODIAC) offers monthly gridded fossil CO_2 emissions (Oda et al., 2018). These products are extremely valuable for their near-real-time performance, but they primarily focus on CO_2, leaving out CH_4 and N_2O entirely. CAMS-GLOB-ANT does cover the other gases, but its sectors are built for air quality modelling, not for emission accounting (Soulie et al., 2024).

Taken together, these two existing approaches leave a glaring gap that hampers both climate science and effective action. There is currently no global dataset that delivers three essential features at the same time: full coverage of all three major greenhouse gases from the energy sector, updates that are fast enough to capture the current year's developments, and a solid basis in measured or reported statistical records. Near-real-time data on emissions of all three greenhouse gases would help us

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understand the impacts of sudden events on emissions (global pandemics, economic crises, energy supply shocks, or lockdowns) almost as they unfold, and inform the design of green recovery packages that prevent a rebound in high-polluting sectors (Le Quéré et al., 2020; Liu et al., 2022; Dou et al., 2022). Without a reliable, multi-gas, near-real-time dataset, our picture of the planet's condition remains incomplete, and policy responses may be delayed or misinformed.

In this study, we introduce a new dataset designed to fill exactly this gap. The dataset is classified by reporting entity, sector, fuel, and gas. The emissions data for historical years (1960–2023) is calculated with IEA activity data and emission factors. Building on the historical emissions data, we develop a framework for forecasting emissions data that includes several candidate prediction methods. Using this framework, we evaluate the performance of the candidate methods for each entity, sector, and gas using data from 2019–2023 and select the best method to predict emissions for 2024–2025. The selected methods are used to estimate annual emissions for 2024 and 2025, which are then allocated across the 12 months using monthly activity patterns. The result is a dataset that covers 153 reporting entities and provides monthly emissions of CO_2, CH_4, and N_2O classified by reporting entity, sector, fuel, and gas. By uniting speed, multi-gas coverage, and statistical grounding, this data product makes it possible for researchers and decision-makers to track the energy sector's climate footprint almost as it happens.

2 Methods

2.1 Methodology overview

The dataset is constructed in the following three stages (Fig. 1). The first stage calculates the annual emissions from 1960 to 2023. For each cell of a specific entity, sector, fuel, gas, and year, the emission is obtained by multiplying the activity data by the corresponding emission factor. The second stage estimates the annual emissions for 2024 and 2025 using more timely monthly production activity statistics. The third stage allocates the annual emissions across the 12 months of each year using monthly activity indicators.

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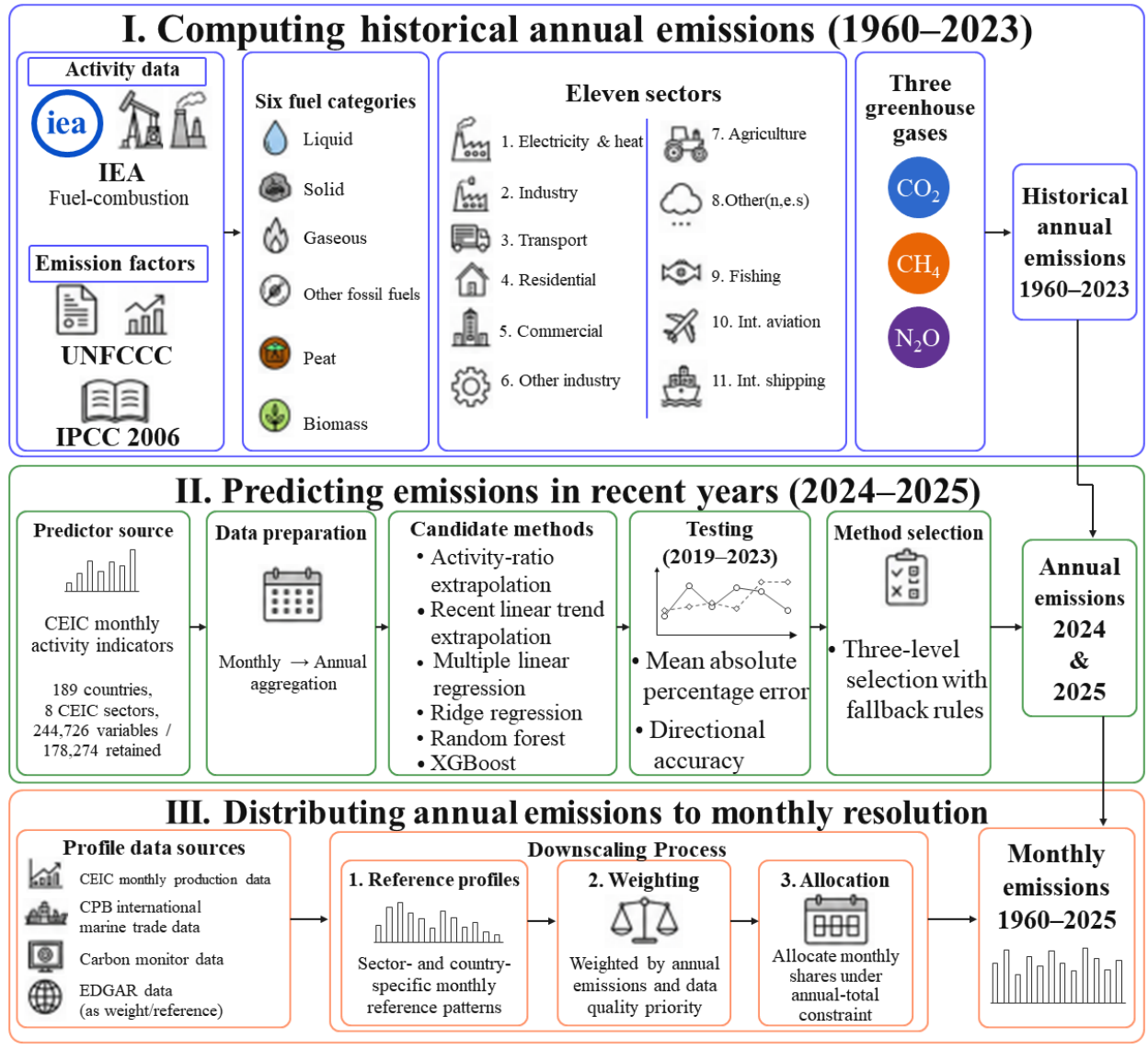


Figure 1: Overview of the method that consists of three stages.

2.2 Annual emissions for 1960 to 2023

Annual emissions (E) for 1960 to 2023 are computed for each reporting entity (r), sector (s), fuel category (f), gas (g) and year (y). The emissions are computed by multiplying the activity data by emission factors. The activity data refers to fuel consumption while the emission factor represents the quantity of a specific gas emitted per unit of the fuel.

$$E_{r,s,f,g,y} = AD_{r,s,f,y} \times EF_{r,s,f,g,y} \quad (1)$$

where AD is the activity data and EF is the emission factor.

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Activity data comes from IEA World Energy Balances 2024 edition (IEA, 2024). Since the IEA's sector classification system differs from IPCC's system, we map the IEA categories that describe energy use to the corresponding fuel-combustion sectors under IPCC category classification. The released sectors and their correspondence to 2006 IPCC categories are provided in Supplementary Table S1.

The difference in data classification between IEA and IPCC results in the omission of certain industrial sub-sectors, and the "Other industry" category in the UNFCCC CRT reports was used to fill the gaps. Since statistics of the "Other industry" category are only available from 1990, there is a slight discontinuity in the data prior to that year. Another caveat is the insufficiency of activity data from the IEA for years before 1970. Therefore, although our dataset covers years 1960 to 2025, we focus our analysis on 1971 onward. How IEA energy products are mapped to the 6 fuel categories (solid fuels, liquid fuels, gaseous fuels, peat, biomass, and other fossil fuels) are provided in Supplementary Table S2.

For the 153 countries and entities in this dataset, we use two sources of emission factors: country-specific emission factors derived from the UNFCCC Common Reporting Tables (CRTs) and the IPCC 2006 default factors (UNFCCC, 2025; IPCC, 2006). Of the 96 reporting parties covered by the CRT, 90 are also among the 150 countries reported individually in the IEA data. We therefore applied country-specific emission factors for these 90 countries. For the remaining 60 individually reported countries, the residual entity of the 48 other countries and territories, and international aviation and shipping, we use the IPCC 2006 default emission factors (IPCC, 2006; Banja et al., 2025). Details regarding the CRT coverage used for factor extraction are provided in Supplementary Table S4. For years preceding the first CRT record of a given country, we apply the country's earliest available emission factor instead. Biomass CO_2 is reported separately and excluded from the fossil CO_2 total by inventory convention, while biomass CH_4 and N_2O are included (IPCC, 2006).

2.3 Predicting annual emissions for 2024 to 2025

The IEA World Energy Balances for 2024 and 2025 had not been released when this study was conducted. Therefore, we use more recent activity indicators, such as industrial production and electricity generation, to estimate emissions for these two years. These activity indicators are primarily taken from the CEIC Data monthly database (CEIC Data, 2026). The entire procedure to predict emissions involves three steps.

First, we began by identifying which activity indicators were appropriate for predicting emissions. The initial pool contains 244,726 monthly indicators drawn from the CEIC Data monthly database (CEIC Data, 2026). We first filtered for series with complete monthly observations throughout 2019–2025, which leaves 178,274 candidates. Since prediction is performed at annual resolution, the monthly CEIC indicators are first aggregated into annual figures. Next, we select indicators based on how closely they represent the sector being predicted. The indicators that directly describe activity in that sector are prioritized. For instance, the electricity generation is used for the power sector, and industrial production is used for manufacturing. If these indicators are unavailable, we use broader indicators related to the sector, such as national energy demand or economic activity metrics. As fallback indicators do not directly represent the conditions of the target sector, they were used only when

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more specific indicators are unavailable. 138 of the 150 individually reported countries are covered by the CEIC, and 12 other countries use the fallback pool directly (Supplementary Table S7).

Second, after selecting the activity indicators, we determine the most suitable approach for predicting emissions for each country, sector, and gas combination. There are six candidate methods: intensity scaling, linear trend extrapolation, multiple linear regression (MLR), ridge regression, random forest (RF), and XGBoost.

For intensity scaling, emissions in the target year *t* are estimated as

$$E_t = A_t \times \frac{E_{t-1}}{A_{t-1}} \quad (2)$$

where E_{t-1} is the emission in the preceding year, and A_{t-1} and A_t are the selected activity indicator in the preceding and target years, respectively. Linear trend extrapolation fits a linear trend to the historical emission series and extends it to the target year. MLR, ridge regression, RF, and XGBoost utilize the selected annual activity indicators to predict annual emissions. Additionally, two constraints apply. Linear trend extrapolation, MLR, ridge regression, RF, and XGBoost require at least 10 years of training data, and XGBoost is used only when at least two activity indicators are selected.

Third, we used known emission data from 2019 to 2023 to jointly test the candidate activity indicators and the candidate prediction methods and to find the best way to predict for each country, sector, and gas combination. Specifically, the decision is made based on the evaluation results, following a three-level hierarchy. First, if a single method performs exceptionally well, with a mean absolute percentage error (MAPE) less than 5%, and a directional accuracy of at least 80%, the method is adopted directly. Second, if no single method meets the standard, we experiment with different ensembles of single models as well as refining through iterative addition or removal of indicators. Third, if the criterion of MAPE less than 5% and directional accuracy of at least 80% cannot be fulfilled, we use the value in 2023 as the fallback option.

2.4 Monthly allocation

Annual emissions for the period from 1960 to 2025 are distributed across the 12 months of the year using monthly activity indicators. For each reporting entity and sector, the resulting monthly distribution pattern is applied to all fuel categories and gases.

For each reporting entity and sector, we select a monthly activity indicator and calculate the share of each month's activity in the annual activity. These monthly shares are then used to distribute the annual emissions across the 12 months, as shown in Eq. (3) and Eq. (4).

$$E_{r,s,m,y} = w_{r,s,m,y} \times E_{r,s,y} \quad (3)$$

$$w_{r,s,m,y} = \frac{I_{r,s,m,y}}{\sum_{m'=1}^{12} I_{r,s,m',y}} \quad (4)$$

where index r is the reporting entity, s is the sector, m is the month, and y is the year. $E_{r,s,y}$ denotes the annual emissions of sector s, while $w_{r,s,m,y}$ represents the monthly share of sector s within the year.

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These monthly activity profiles are selected from four sources in a fixed order of priority. First, for the power and industrial sectors, monthly indicators from CEIC are applied when available. Second, monthly characteristic data for international shipping are obtained from CPB World Trade Monitor (CPB, 2026). Third, data from Carbon Monitor (Liu et al., 2020; Dou et al., 2022) are used from 2019 onward for covered power, industry, transport, residential, and aviation sectors. Finally, if data from the aforementioned high-priority sources are not available, EDGAR (Crippa et al., 2024) monthly profiles are adopted for years after 1970. For years before 1970, we use the 1970 EDGAR monthly profile. Supplementary Table S6 provides a summary of data used for monthly allocation.

2.5 Calculation of uncertainty

The calculation of uncertainty for this dataset follows the uncertainty propagation method from IPCC (2006). The emission value for 1960–2023 is obtained by multiplying the activity data by the corresponding emission factor. Hence, the uncertainty for the emissions, defined as the half-width of the 95% confidence interval, can be easily calculated as the square root of the sum of the squares of the relative uncertainties. Uncertainty values for activity data are drawn from IPCC (2006): ±5% for industrialized countries and ±10% for developing countries. The classification of countries into industrialized and developing countries follows the split in the EDGAR dataset (Janssens-Maenhout et al., 2019). Uncertainties of emission factors are also drawn from IPCC (2006): ranging from ±3.9% to ±32% for CO_2 and from ±40% to ±150% for CH_4 and N_2O. Admittedly, the uncertainties for 2024 and 2025 predictions are difficult to calculate directly, as they inherit the uncertainties of the inputs and the prediction methods. Furthermore, the inputs and the selected prediction methods differ across each combination of sector, country, and fuel, making it difficult to calculate. Hence, we use 2023's relative uncertainty as the estimate of the uncertainties for 2024 and 2025.

When aggregating emissions across countries, sectors, and fuel types, we apply the rules established by Solazzo et al. (2021) for the EDGAR dataset. For emissions that share the same IPCC default emission factor, the errors are correlated so the uncertainties are summed directly. For countries that self-report emission factors to the UNFCCC, the errors are not correlated with errors of other countries, so the uncertainties are combined using the square root of the sum of squares. When relative uncertainty exceeds 100%, subtracting the uncertainty from the estimate would result in negative emissions, so we provide upper and lower bounds based on the log-normal method from IPCC (2006). The relative uncertainties are categorized into six levels following Solazzo et al. (2021): 0–10% (high), 10%–20% (medium-high), 20%–40% (medium), 40%–60% (medium-low), 60%–100% (low), and >100% (very low).

3 Results

3.1 Overview of the released dataset

This dataset reports fuel-combustion emissions of CO_2, CH_4, and N_2O from 1960 to 2025, resolved simultaneously by entity, sector, fuel category, and gas (Niu et al., 2026). For entities, the dataset contains 153 reporting entities, which consist of 150

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individually reported countries, one residual entity grouping 48 other countries and territories that do not report individually to the IEA, international aviation, and international shipping (Supplementary Table S3). For sectors, the dataset has 11 mutually exclusive top-level sectors, and a total of 36 sectors that include the top-level sectors and their subsectors. For fuel, the dataset includes six different fuel categories: solid fuels, liquid fuels, gaseous fuels, peat, biomass, and other fossil fuels. The complete release inventory is summarized in Table 1. The column names, meanings and units in the dataset are specified in Supplementary Table S5.

Table 1: Complete release inventory of the dataset.

Item	Description
Year coverage	1960–2025
Finest time resolution	Monthly
Reporting entities	153 total (150 individually reported countries, one entity including 48 countries and territories that did not report individually to the IEA, international aviation, and international shipping)
Sectors	36 values (11 mutually exclusive top-level sectors plus their subsectors)
Fuel categories	6 different categories: Solid fuels, Liquid fuels, Gaseous fuels, Peat, Biomass, and Other fossil fuels
Greenhouse gases	CO_2, CH_4, and N_2O (in physical mass units)
Accounting boundary	Emissions from fuel combustion (IPCC Category 1.A). This excludes fugitive emissions from coal, oil, and gas systems, as well as cement production and other emissions outside fuel combustion.

3.2 Long-term emission trends

Emissions from all three gases have risen overall in the past half-century, but with different trajectories (Fig. 2). The global CO_2 emission shows a general increasing trend, rising from 12.8 Gt in 1971 to 37.7 Gt in 2025, but it also contains dips. For example, CO_2 emissions decreased from 35.5 Gt in 2019 to 33.4 Gt in 2020 and bounced back to 35.3 Gt in 2021. Global N_2O also shows an overall increasing trend from 455 kt in 1971 to 1,057 kt in 2025, but the overall speed of the increase is slower than that of CO_2. In contrast, CH_4 follows an early peak trend. The CH_4 emissions rose from 8.6 Mt in 1971 to a peak of 11.7 Mt in 1990 and then declined and remained near around 11 Mt.

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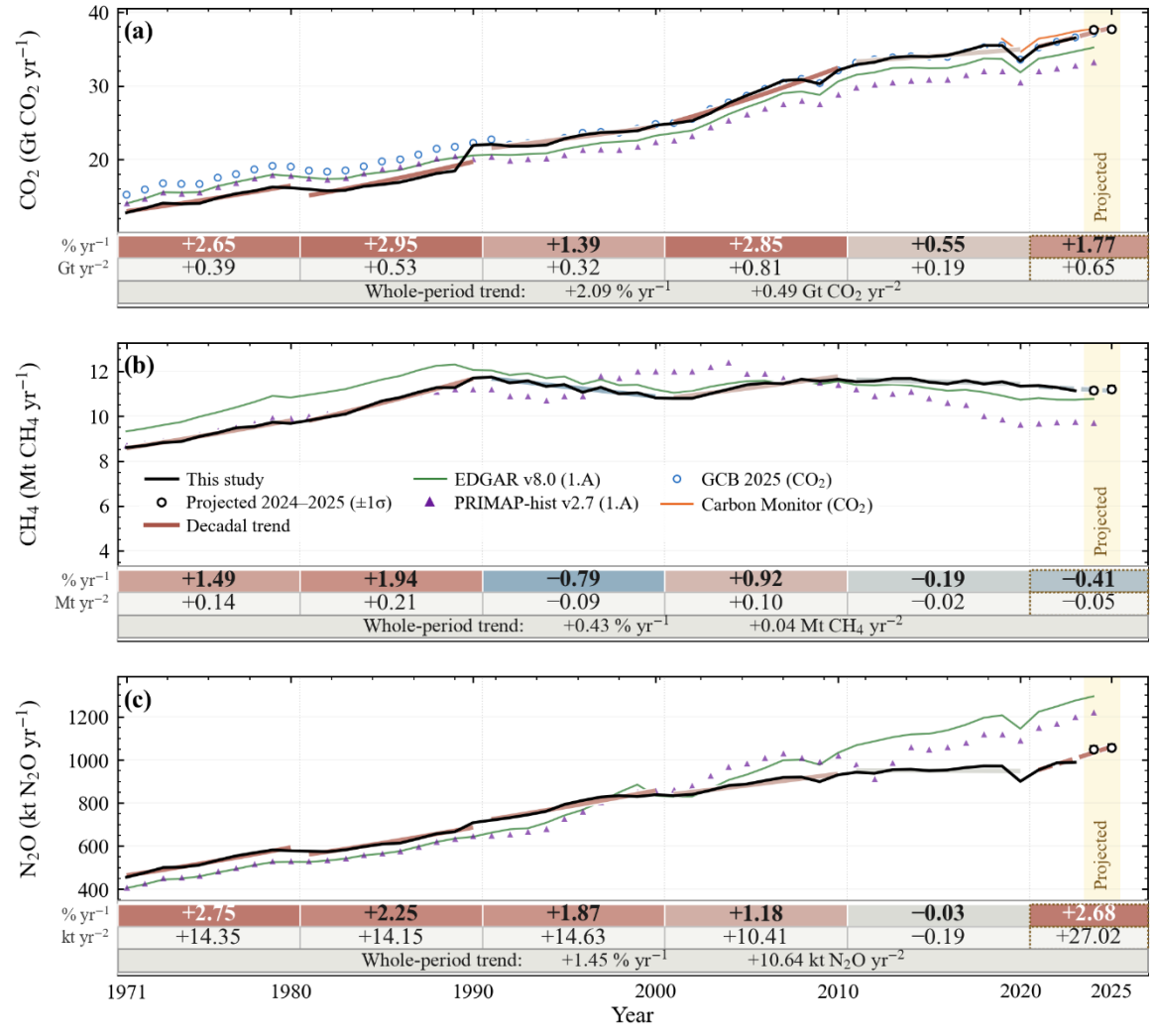


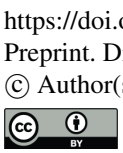
Figure 2: Global annual time series of CO_2 (Gt CO_2 yr^{-1}), CH_4 (Mt CH_4 yr^{-1}) and N_2O (kt N_2O yr^{-1}) respectively. Annual reference series overlaid on all three panels: EDGAR v8.0 (Crippa et al., 2024), PRIMAP-hist v2.7 (Gütschow et al., 2016, 2025). The CO_2 panel additionally overlays the Global Carbon Budget 2025 fossil totals excluding cement (Friedlingstein et al., 2026) and the Carbon Monitor world series (Liu et al., 2020; Dou et al., 2022).

3.3 Seasonal variation of emissions

This section reports on emission variations within a year for each of the six fuel categories (Fig. 3) across the 9 top-level sectors. The analysis excludes the 2 other top-level sectors, international aviation and shipping, because their monthly coefficient of variation is below 1%. Figure 3a presents each fuel's monthly deviation from its 12-month average over 1971–2023.

All six fuels share a winter-peak and summer-trough pattern, but the amplitudes of the variations differ. Biomass exhibits the strongest seasonal variations with a range of 128% of its annual monthly average (January +89.5%, September −38.8%),

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followed by peat (range 67%), gaseous fuels (range 51%), other fossil fuels (range 32%), liquid fuels (range 21%), and solid fuels (range 17%). The results demonstrate that the largest fuels by share have the smallest seasonal variations: liquid fuels (42% share) and solid fuels (38% share) together account for about 81% of climatology emissions but show only 21% and 17% seasonal ranges, whereas biomass, the most seasonal fuel, contributes just 1.1%.

Figure 3b shows the deviation of 2024–2025 monthly emissions from the 1971–2023 climatology. Five fuels lie above the climatology, and only peat lies below. Other fossil fuels show the largest positive deviation (annual mean +179%, monthly range +154% to +210%), followed by gaseous (+81%), solid (+62%), liquid fuels (+38%), biomass (+17%), and peat (−45%). The positive deviations here primarily reflect the long-term growth in emissions rather than changes that are specific to 2024–2025 because the 1971–2023 climatology includes earlier periods when global emissions were far below current levels. Among all the fuel categories, peat is the only one that has a decreasing trend.

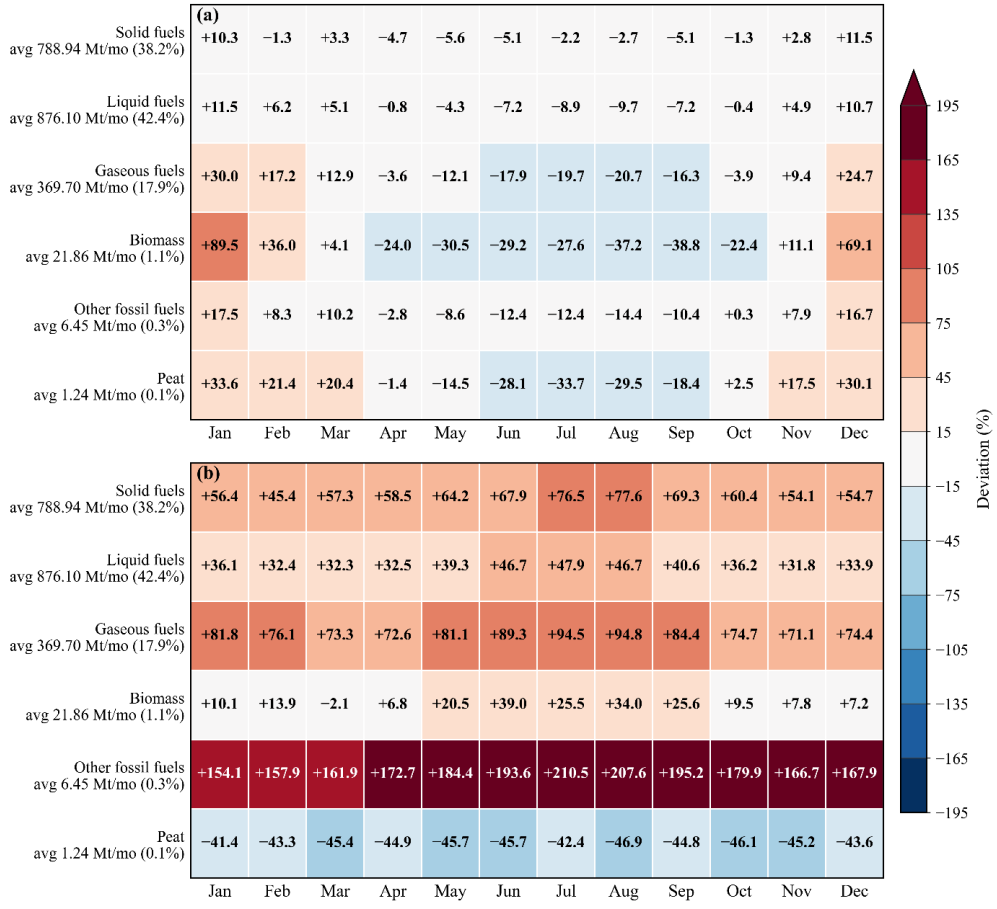
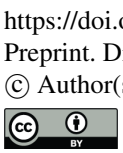


Figure 3: Monthly heatmaps for the six fuel categories used in the dataset. From top to bottom, the rows represent solid fuels, liquid fuels, gaseous fuels, biomass, other fossil fuels, and peat. (a) Monthly climatology pattern, 1971–2023. Each cell shows the relative deviation of the monthly mean from the corresponding fuel's 12-month average, calculated as (month value − 12-month average) / 12-month average × 100%. (b) Changes of 2024–2025 monthly emissions relative to the 1971–2023 climatology, computed as (2024–2025 month value − climatology month value) / climatology month value × 100%. The diverging color map in both panels is centered at zero. CO_2-equivalent values use AR6 GWP-100 with fossil CH_4 = 29.8 and N_2O = 273 (Forster et al., 2021).

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3.4 Recent emissions analysis by region

Recent emission trends have differed markedly across global regions (Fig. 4). There is a clear geographic split between growth and decline. Compared with the 2016–2023 mean, Eastern Asia, Southern Asia, Southeast Asia and developing Pacific, Middle East, and Africa have higher emissions in 2024–2025. Europe, North America, Latin America and the Caribbean, and Asia-Pacific Developed have lower emissions in 2024–2025. Eurasia is the only region that remained almost the same (+0.9%). Southern Asia has the largest relative increase at 13.2% (2,731 to 3,090 Mt CO_2eq yr^{-1}). Eastern Asia has the largest absolute increase, with a +983 Mt CO_2eq yr^{-1} (+9.7%). Eastern Asia remains the highest-emitting region, accounting for 34% of the total emissions among the 10 regions. Europe has both the largest relative and absolute decrease in emissions with −590 Mt CO_2eq yr^{-1} (−17.4%).

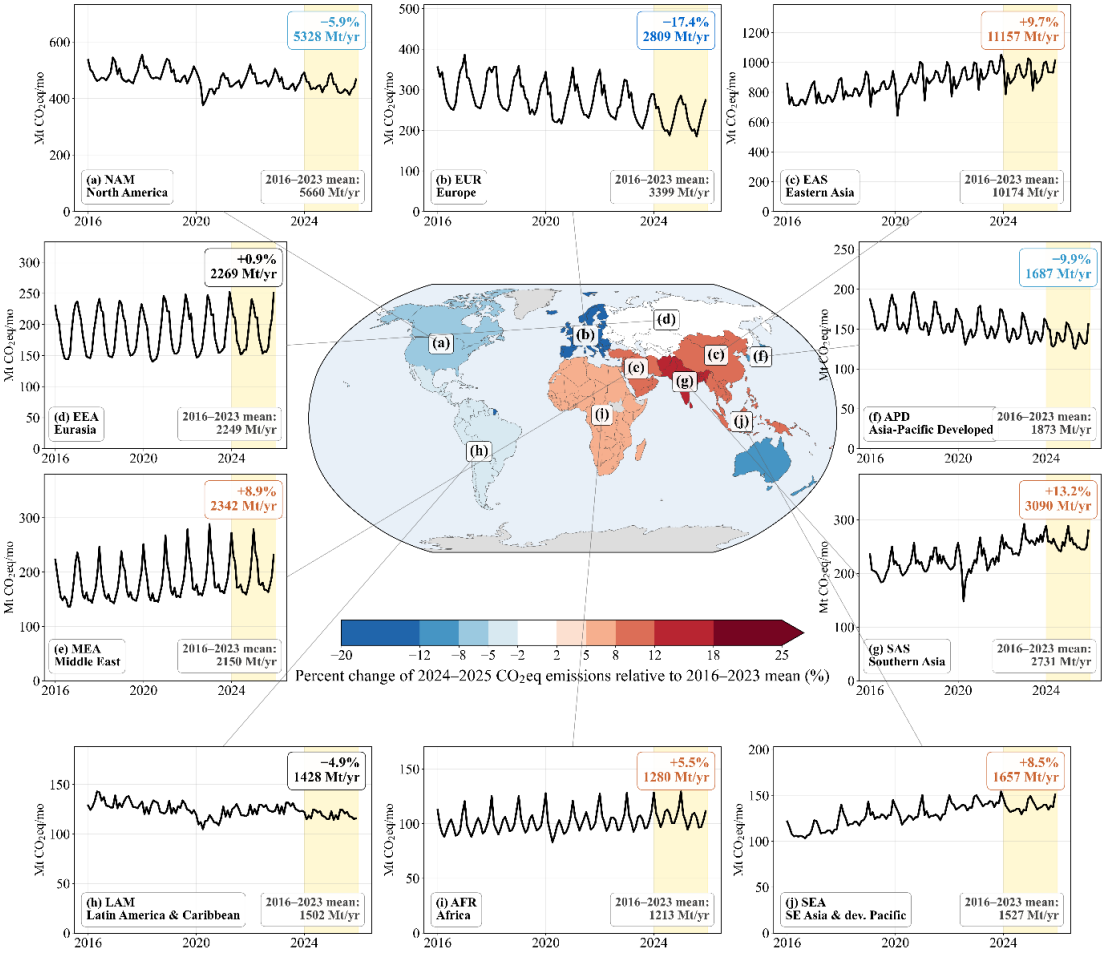


Figure 4: Regional fuel-combustion emission changes in 2024 and 2025 relative to the 2016–2023 baseline, organized by the ten regions of the IPCC AR6 WG3 R10 classification (Al Khourdajie et al., 2022). The change is given in the relative change of the 2024–2025 mean against the 2016–2023 baseline. Each region panel reports the region's relative change in percentage and absolute change (Mt CO_2eq yr^{-1}) and contains a monthly trend of CO_2-equivalent emissions for 2016–2025 with the 2016–2023 baseline marked. Region panels: (a) North America (NAM), (b) Europe (EUR), (c) Eastern Asia (EAS), (d) Eurasia (EEA), (e) Middle East (MEA), (f)

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Asia-Pacific Developed (APD), (g) Southern Asia (SAS), (h) Latin America and the Caribbean (LAM), (i) Africa (AFR), (j) Southeast Asia and developing Pacific (SEA). The Other Countries (48) residual entity (OTH), international aviation (IAV) and international shipping (ISH) are excluded from the regional aggregation. CO_2-equivalent values use AR6 GWP-100 with fossil CH_4 = 29.8 and N_2O = 273 (Forster et al., 2021).

3.5 Comparison with other datasets

We compare our dataset with four reference datasets: the Global Carbon Budget (GCB) 2025 (Friedlingstein et al., 2026), PRIMAP-hist v2.7 HISTCR scenario (Gütschow et al., 2016, 2025), UNFCCC submissions (UNFCCC, 2025) and Carbon Monitor (Liu et al., 2020; Dou et al., 2022). The first three comparisons (Fig. 5a–c) use year 2021 for comparison because it has the broadest UNFCCC coverage among years between 2019 and 2023, whereas the monthly comparison (Fig. 5d) spans the period from January 2019 to December 2025.

For CO_2, the dataset presented in this study shows high correlation with GCB, PRIMAP-hist v2.7 HISTCR, and UNFCCC data, with R^2 ranging from 0.97 to 0.99 and mean normalized bias (MNB) between −13.8% and +4.2%. For N_2O, the dataset also shows a strong correlation with PRIMAP-hist v2.7 HISTCR and UNFCCC having R^2 values of 0.88 and 0.92 and MNB values of +22.8% and +10.1% respectively. For CH_4, the dataset correlates well with UNFCCC with R^2 value of 0.91 and a MNB of +11.5% but shows a weaker correlation with PRIMAP-hist v2.7 HISTCR with R^2 value of 0.77 and a MNB of +192.4%. This outlier is primarily driven by the difference of emissions from India. Our dataset reports 1.66 Mt yr^{-1} while PRIMAP-hist v2.7 HISTCR reports 0.36 Mt yr^{-1}. India's submission to UNFCCC is 1.42 Mt yr^{-1} which is closer to ours.

Regarding fuel composition, we compared our dataset with UNFCCC data to see if the share of each of the three main fuel categories (solid, liquid, and gaseous) corresponds to UNFCCC's share. For the top 15 emitting countries combined, all three main fuel categories are within 10% difference with the UNFCCC data. Finally, we also compared the monthly patterns of our dataset with Carbon Monitor. To avoid circular validation, the comparison specifically excluded records derived from Carbon Monitor. Among the top 20 reporting entities by emission volume, 10 countries exhibit monthly R^2 exceeding 0.85. A few countries show weaker agreement: Brazil, Poland, and Austria have R^2 values below 0.70, while Spain's data deviates significantly with an R^2 value of 0.15. The global total agrees well with Carbon Monitor, having a monthly R^2 of 0.95.

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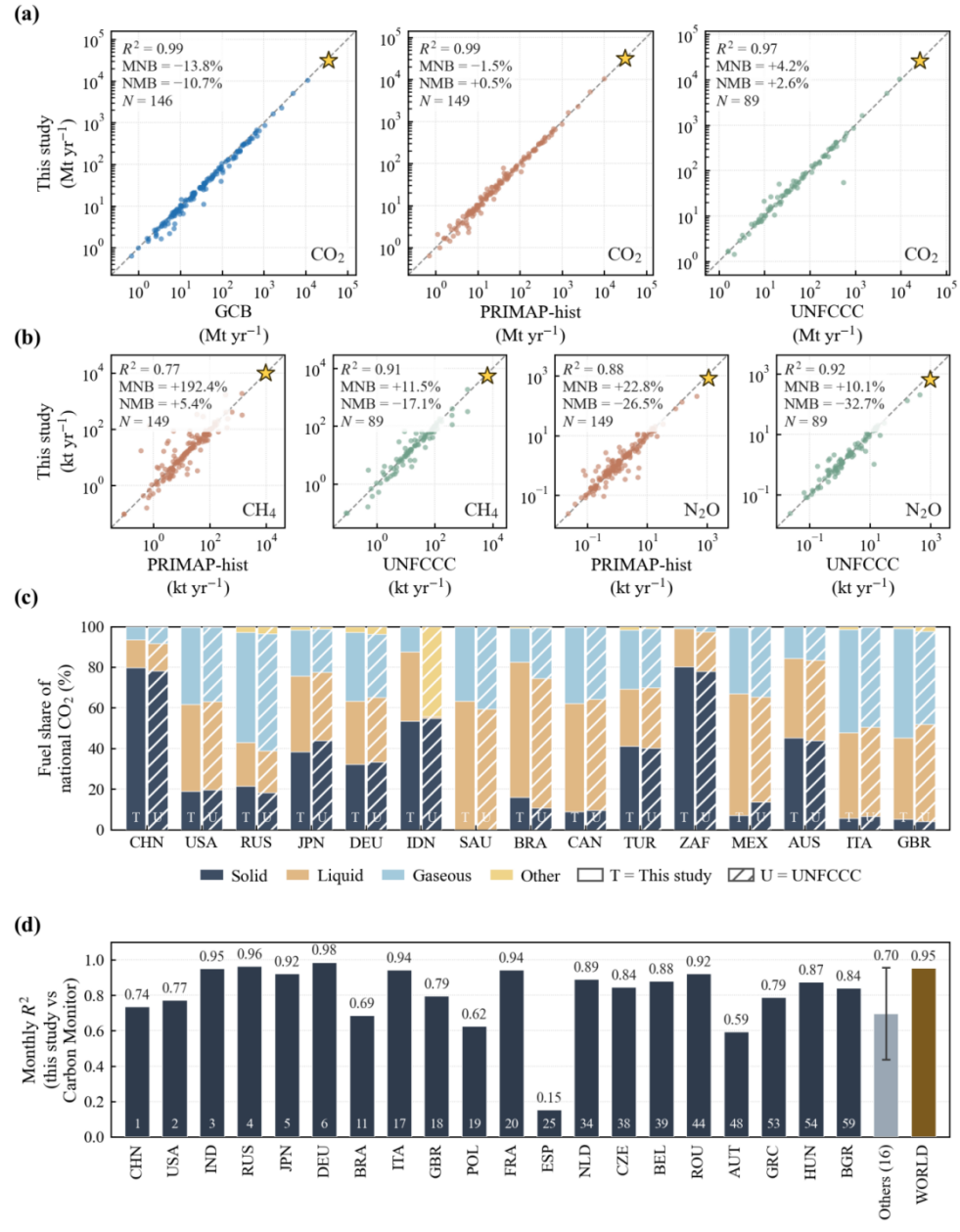


Figure 5: Scale-matched validation of the released records against reference datasets. Panels (a) to (c) use year 2021, the year with the broadest coverage of UNFCCC CO_2 between 2019 and 2023. Panel (d) uses monthly data from January 2019 to December 2025. (a) Scatter plots comparing CO_2 at country scale against GCB, PRIMAP-hist v2.7 HISTCR, and UNFCCC submissions for all reporting entities with data overlap. (b) Scatter plots comparing CH_4 and N_2O at the country-gas scale against PRIMAP-hist v2.7 HISTCR and UNFCCC submissions for all reporting entities with data overlap. The R^2, the mean normalized bias (MNB), and the normalized mean bias (NMB), and the number of paired entities N are reported in panels (a) and (b). (c) Bar charts of fuel shares of national CO_2 for the top 15 highest emitting entities, compared against UNFCCC submissions. (d) Monthly R^2 between the dataset of this study and Carbon Monitor for CO_2 emissions during the period of January 2019 to December 2025. The plot displays the top 20 highest emitting entities individually, one bar representing the remaining entities, and one bar representing the global total. The

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comparison in panel (d) is restricted to records whose monthly profile is independent of the Carbon Monitor source, consistent with the restriction stated in Sect. 2.4.

4 Uncertainty and limitations

4.1 Uncertainty

Across the three gases, the relative uncertainty of global totals differs by an order of magnitude with CO_2 having the lowest relative uncertainty and CH_4 having the highest (Fig. 6). Taking year 2025 as an example, CO_2 has a relative uncertainty of 4.1%, N_2O has a relative uncertainty of 31%, and CH_4 has a relative uncertainty of 58%. As for the trend over time, the uncertainties of the three gases are all increasing since 1971, with the uncertainty of CO_2 rising from around 3% to about 4%, the uncertainty of N_2O rising from roughly 23% to about 31%, and the uncertainty of CH_4 rising from about 40% to around 58%. The overall increasing trend is mainly due to the increase of shares of emissions for developing countries. The around 3% to 4% uncertainty of CO_2 in our dataset is lower than the 7.1% from EDGAR (Solazzo et al., 2021) and the ±10% (2σ) of Global Carbon Budget (Friedlingstein et al., 2026). This is because 71% of the CO_2 emissions in this dataset use nationally reported emission factors, with uncorrelated errors across countries that partially offset upon aggregation.

The relative uncertainty of each sector is highly dependent upon what type of fuel the sector burns and the source of the emission factor. Since the uncertainties in CO_2 emission factors for the three primary fuel types (coal, oil, and gas) are all within ±8% together with the fact that the uncertainty of any activity data is within 10%, 10 out of the 11 primary sectors exhibit an uncertainty within ±10% for CO_2. The only exception is international shipping, which has an uncertainty of ±25% for CO_2. Since emission factors of CH_4 and N_2O from biomass combustion have an uncertainty of ±150%, the sectors that have biomass as a major fuel category have a higher relative uncertainty. CH_4 has a relative uncertainty of ±60% to ±90% in sectors like residential, agriculture, forestry, and fisheries, while the relative uncertainty for N_2O in the residential sector is ±99%. For sectors that primarily rely on fossil fuels and use self-reported emission factors, like transportation, the relative uncertainties of CH_4 and N_2O are all within ±20%.

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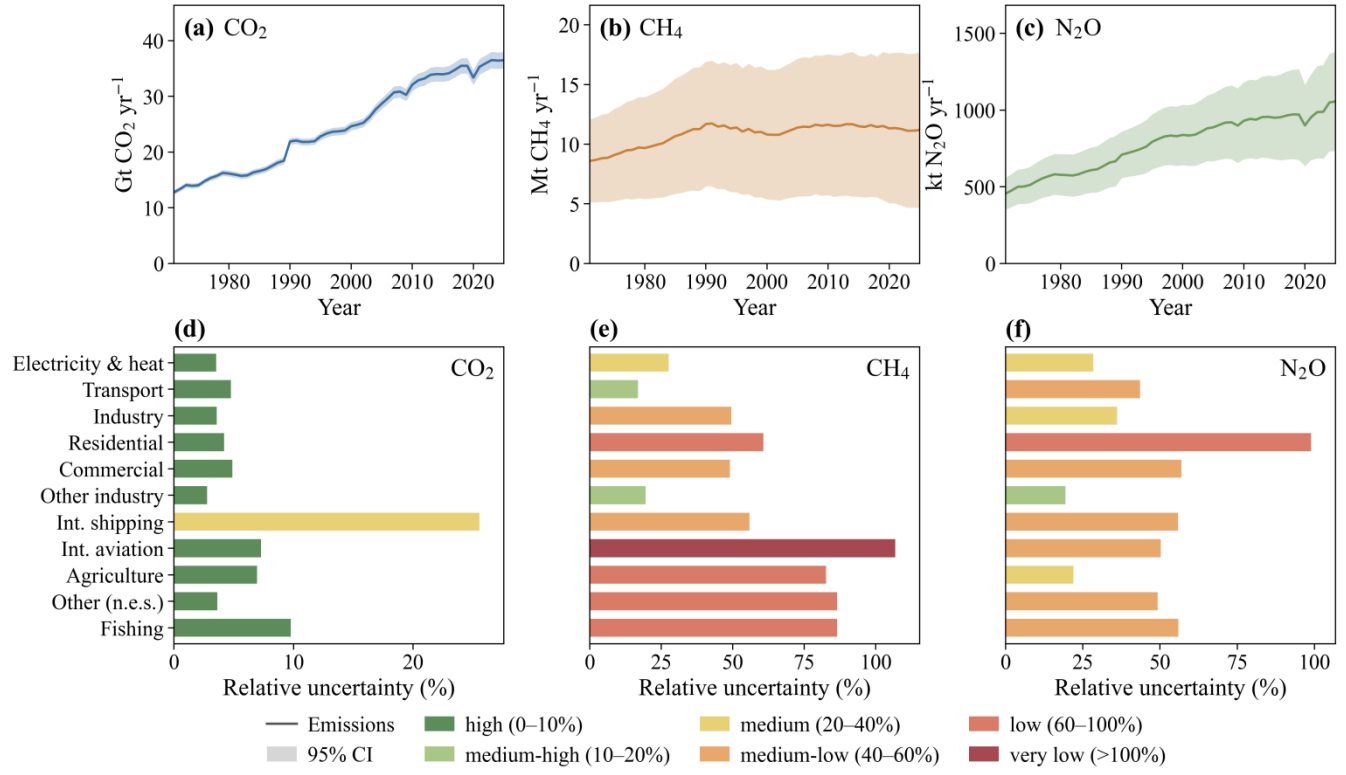


Figure 6: Relative uncertainty of the dataset. (a–c) Global emissions of CO_2, CH_4 and N_2O for 1971–2025, and the shaded areas represent 95% confidence intervals. (d–f) Average relative uncertainty for the 11 top-level sectors over 1971–2025. Colors represent the confidence levels based on Solazzo et al. (2021).

4.2 Prediction accuracy assessment

Since the 2024 and 2025 ground truth data were not available when we conducted the study, we estimate the performance of our predictions based on the performance of the prediction methods on the evaluation years (2019–2023). The reconstructed emission data, computed as activity data multiplied by emission factors, serve as the ground truth to compare against within the evaluation years. We compute the mean absolute percentage error (MAPE) between the predicted and reconstructed CO_2-equivalent total emissions of the three gases. In Fig. 7, we plot the predicted value against the reconstructed data for the 11 top-level sectors and all top-level sectors total, and we report their MAPE. Disrupted by COVID-19, the sector of international aviation has an R^2 of 0.017 and a MAPE of 42.0%. All other sectors have a MAPE of less than 10%. Furthermore, excluding international aviation and shipping, all other sectors have an R^2 higher than 0.99. When considering all sectors, the MAPE is 4.9%, and the R^2 is 0.999 which shows that the prediction methods performed well overall.

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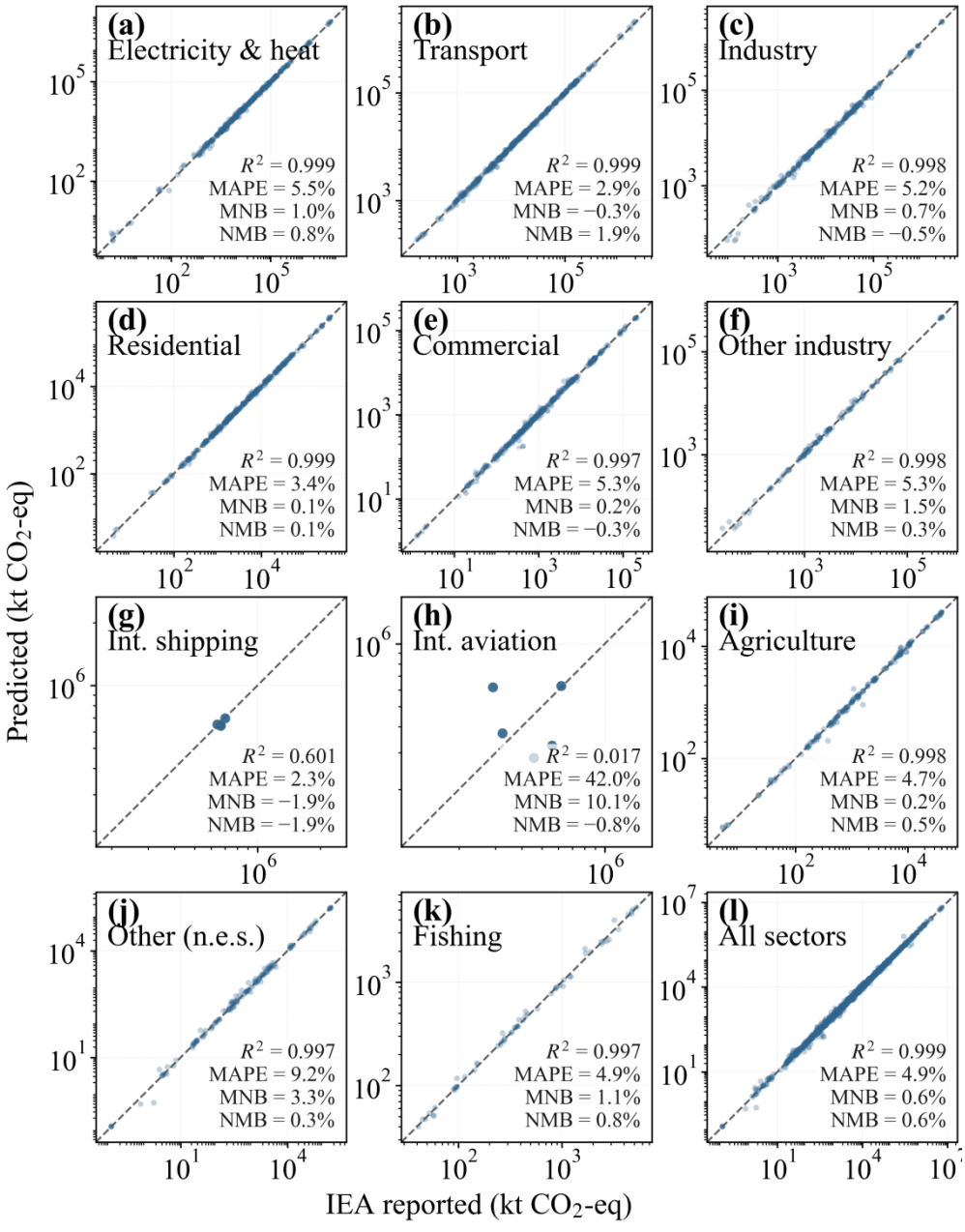


Figure 7: Scatter plots of the predicted value against the ground truth in CO_2 equivalent mass. The graph contains the scatter plots for each top-level sector and a scatter plot for all sectors combined. We report R^2, mean absolute percentage error (MAPE), mean normalized bias (MNB), and normalized mean bias (NMB).

4.3 Limitations and future releases

First, the representativeness of the emission factors varies among the countries. Of the 150 individually reported countries, 90 are matched to country-specific factors from UNFCCC inventory reporting tables, while the remaining 60 countries, together

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with the residual entity, international aviation, and international shipping use IPCC 2006 default factors. Although these 60 countries only account for a small share of the global emission total, many of them have shown a trend in increasing their shares. Future research should collect and establish suitable emissions factors to improve the accuracy of accounting for their emissions.

Second, a small fraction of 2024 and 2025 estimates use the recent-year fallback rule because of the insufficient monthly activity indicators to represent that specific country, sector, and fuel combination. For instance, the residential biomass sector in five developing countries (Ethiopia, Pakistan, Tanzania, Kenya, Uganda) and part of Iran's residential and industrial CO_2 mainly use 2023's value in 2024 and 2025 because the monthly activity indicators pool here does not directly cover household biomass demand. However, the influence on the global total is limited because of the relatively small share that these cases represent within the total global emissions. Future research can extend the monthly activity indicators pool to indicators of household biomass demand in developing countries.

Third, the monthly values are restricted by the annual total, since monthly values are derived from distributing the annual total. The choice of monthly profile indicators does not change the annual totals but only affects the month-to-month variability. The precision of the monthly values is, therefore, not only highly dependent on the monthly profile indicators but also on the accuracy of the annual value. Records assigned to the EDGAR climatological baseline carry larger seasonal uncertainty than records using year-specific monthly activity profiles from CEIC, CPB, or Carbon Monitor. Monthly variations in emissions should be interpreted in light of the data sources used to distribute annual emissions across months.

5 Conclusions

This dataset reports monthly fuel-combustion emissions of CO_2, CH_4, and N_2O from 1960 to 2025, organized by reporting entity, sector, fuel, and gas. It covers 153 reporting entities, 36 sectors (11 mutually exclusive top-level sectors and their subsectors), and 6 different fuel categories. The accounting boundary is restricted to emissions from fuel combustion. Records for 1960 to 2023 are computed from IEA fuel-combustion activity data and emission factors from UNFCCC Common Reporting Tables and IPCC 2006 default factors. Records for 2024 and 2025 are predicted using prediction methods based on past emission data and CEIC monthly activity indicators. Comparisons with existing datasets including Global Carbon Budget, PRIMAP-hist, UNFCCC submissions, and Carbon Monitor demonstrate good consistency after accounting for differences in emission coverage. This dataset can be used for carbon budget tracking, Nationally Determined Contributions (NDCs) and Global Stocktake assessment, sector-level near-real-time monitoring, and structured bottom-up input to atmospheric chemistry and inverse modelling at country, sector, fuel, and monthly scales for fuel combustion emissions.

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Data availability

The dataset that supports the findings of this study has been deposited in Zenodo at https://doi.org/10.5281/zenodo.23104477 (Niu et al., 2026). Access to the data has been granted to reviewers and editors and will be made openly available upon acceptance. For members of the public interested in participating in the public discussion, the data are available upon request (contact: yuanwp@pku.edu.cn) during the review period. The IEA World Energy Balances and the CEIC monthly database are available under license at https://www.iea.org/data-and-statistics/data-product/world-energy-balances (IEA, 2024) and https://www.ceicdata.com (CEIC Data, 2026), respectively. The UNFCCC Common Reporting Tables are available through the First Biennial Transparency Reports at https://unfccc.int/first-biennial-transparency-reports and the National Inventory Submissions 2025 at https://unfccc.int/ghg-inventories-annex-i-parties/2025 (UNFCCC, 2025). The IPCC 2006 default emission factors are available at https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html (IPCC, 2006). The CPB World Trade Monitor is available at https://www.cpb.nl/en/world-trade-monitor/cpb-world-trade-monitor-january-2026 (CPB, 2026). Carbon Monitor data are available at https://carbonmonitor.org (Liu et al., 2020; Dou et al., 2022). The EDGAR monthly emissions and temporal profiles are available at https://doi.org/10.2905/b54d8149-2864-4fb9-96b9-5fd3a020c224 (Crippa et al., 2024) and https://edgar.jrc.ec.europa.eu/dataset_temp_profile (Crippa et al., 2026). The Global Carbon Budget national emissions and PRIMAP-hist v2.7 used for comparison are available at https://doi.org/10.18160/GCP-2025 (Friedlingstein et al., 2026) and https://doi.org/10.5281/zenodo.17090760 (Gütschow et al., 2016, 2025), respectively.

Author contributions

Hanlin Niu: Conceptualization, Methodology, Software, Data curation, Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing. Jiaying Fu: Data curation, Validation, Visualization, Writing – review & editing. Miao Huang: Data curation, Validation. Xi Li: Conceptualization, Methodology, Software, Data curation, Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing. Xianhong Meng: Supervision, Writing – review & editing. Wenping Yuan: Conceptualization, Methodology, Supervision, Funding acquisition, Writing – review & editing. Shilong Piao: Conceptualization, Supervision.

Competing interests

The authors declare that they have no conflict of interest.

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