The Global Carbon Project's fossil CO_2 emissions dataset: 2023 release (update 1)

Robbie M. Andrew and Glen P. Peters
CICERO Center for International Climate Research
Oslo, Norway

[internal version GCB2023v43]

Contents

The Global Carbon Project's fossil CO_2 emissions dataset: *2023 release (update 1)*

[internal version GCB2023v43]

Robbie Andrew and Glen P. Peters
CICERO Center for International Climate Research
Oslo, Norway
24 January 2024

Abstract

The Global Carbon Project has been publishing estimates of global and national fossil CO_2 emissions since 2001. In the first instance these were simple republications of data from another source, but over subsequent years refinements have been made in response to feedback and identification of inaccuracies. In this article we describe the history of this process leading up to the methodology used in the 2023 release of the GCP's fossil CO_2 emissions dataset, with subsequent updates.

1. Introduction

The Global Carbon Project was established in 2001 and is currently one of 20 Global Research Projects under Future Earth. Its goal is "to develop a complete picture of the global carbon cycle, including both its biophysical and human dimensions together with the interactions and feedbacks between them" (GCP, no date).

The purpose of the GCP's fossil CO_2 emissions dataset has always been as one component of the Global Carbon Budget, the balancing source and sink components of carbon dioxide. In the early years of the GCP the fossil CO_2 emissions dataset was taken directly from CDIAC, the Carbon Dioxide Information Analysis Center of the Oak Ridge National Laboratory (e.g., Raupach et al., 2007). The production of this dataset has since shifted to Appalachian State University and been renamed CDIAC-FF (Gilfillan and Marland, 2021). CDIAC had been producing estimates of global and national fossil CO_2 emissions since 1999, although the history goes back to 1973 with the work of Keeling (1973) and Rotty (1973) (see Andrew (2020a) for further details of this history). CDIAC's emissions estimates have a long-standing presence in the scientific community as well as covering all countries and extending back to 1751 in the early industrial period, and were divided into emissions from solid, liquid, and gaseous fuels as well as venting/flaring and cement production. Some aspects of the methodology used by CDIAC were incorporated into the Tier 1 approach in the first IPCC Guidelines (Haukås et al., 1997). CDIAC applied standard factors to apparent consumption[1] of energy derived from UN energy data, including flared natural gas, and extended these a further two years using growth rates derived from BP's Statistical Review of World Energy. Process emissions from cement production were derived from cement production statistics from the United States Geological Survey. CDIAC therefore provides a solid foundation of global and national fossil CO_2 emissions. However, over the years as queries have come in to the GCP asking for explanations of deviations

[1] Apparent consumption is derived from data on production, exports, imports, and stock changes. It contrasts to observed consumption, collated from alternative sources such as industry reporting of direct consumption or sales to consumers. The Reference Approach to calculating emissions uses apparent consumption of energy products, while the Sectoral Approach uses alternative approaches.

from officially estimated emissions or unusual trends, the GCP's fossil CO_2 emissions dataset has been refined in a gradual process.

This report is largely devoted to a more detailed description of the methods used to assemble the latest version of GCP's fossil CO_2 emissions dataset.

2. Methods

The GCP's fossil CO_2 emissions dataset begins with CDIAC-FF (updated from Hefner and Marland, 2023), extended by 2–3 years using energy growth rates derived from data published by the Energy Institute (EI; formerly by BP) (Myhre et al., 2009; Energy Institute, various years), depending on the availability of CDIAC-FF.

CDIAC-FF uses UN energy data with disaggregated energy types, and after calculating emissions from these, aggregates to a reduced number of categories: solid, liquid, and gaseous fossil fuels, as well as gas flaring and cement process emissions. Note that these allocations are made on the basis of the primary fossil fuel category: e.g., natural gas liquids, some of which are in fact gaseous at standard temperature and pressure, are allocated to the liquid category; and gases made from coal are allocated to the solid category. Emissions from combustion of international bunker fuels are also allocated to each country based on sales by the country, but these are excluded from national totals, following standard international reporting practice. For GCB version 2022v27 we use a pre-release of CDIAC-FF 2022 (pers. comm., Gregg Marland, 26 September 2022).

The Statistical Review of World Energy is released in June or July every year, being the first freely available global update of energy up to the previous year. This dataset was published by BP for many years, until the Energy Institute took over from 2023 (Energy Institute, 2023). Since the UN data used by CDIAC-FF lag by two years, the Statistical Review has proved useful in extending the emissions series (Myhre et al., 2009; Friedlingstein et al., 2020). While EI's data cover global energy consumption, detail is only provided for the most significant countries, with the remaining countries in each geographic area grouped (e.g., 'Other South America'). To use growth rates derived from the EI/BP data to extend emissions estimates, it is therefore necessary to apply the growth rate from each of these groups to all countries falling within the group for which data are not explicitly provided, and this introduces some additional uncertainty.

For a growing number of countries, and also for international bunkers, we have been introducing more specific data sources, gradually (but only slightly) reducing our reliance on the Statistical Review in particular situations where we believe that use of more direct data sources is warranted. For example, we now use JODI data for emissions from natural gas consumption in final years for many countries. The 'Refinements' section of this report lists many other examples.

Our philosophy in the Global Carbon Budget is to obtain the best possible estimate of fossil CO_2 emissions globally, therefore we take the position that accuracy is more important than use of the same method across all countries, with the obvious condition that both double counting and undercounting of emissions are avoided.

Sometimes an argument is made in public discourse and presentation of collated datasets for consistency of data sources and methods as being the best approach when assembling estimates of emissions. Certainly, a strong case can be made that consistent system boundaries should be used when comparing between countries: that the same categories of emissions source are included (Andrew, 2020a). Comparing emissions estimates for two countries when one countries' estimate includes emissions sources such as non-energy uses of fossil fuels and carbonate decomposition, while the other countries' estimate does not is clearly not going to result in a useful comparison. However, when two different methods are used to calculate the same thing, this does not necessarily constitute an 'apples with oranges' comparison. Clearly using data from only one source is convenient and reduces effort, a strong argument in its favour. But the other, sometimes unspoken argument might be that the 'inconsistencies' introduced by using more than one data source will lead to errors. It is this point that we disagree with.

2.1. Nomenclature

Until 2017, GCP referred to the fossil CO_2 emissions as emissions from "fossil fuels and industry", where industry specifically meant process emissions from cement production, using the shorthand "E_{FF}". However, this term has generated considerable confusion among users who often assumed that 'industry' had its normal meaning of those sectors of the economy not involved in agriculture or services, and the question "what about transport emissions?" was not uncommon. This confusion partly stems from a more common division of total emissions into different sectors (power, transport, residential, etc.), in contrast to CDIAC-FF's approach of fuel categories. In fact, most energy data have lower uncertainty when expressed in fuel terms than in terms of which sectors use the energy, which is often further derived from the fuel-level energy data using additional approximations. That said, CDIAC-FF's choice to divide into fuel categories rather than sectors arose simply from the availability of data in the early years: UN data provided little information about sectoral energy consumption. To avoid this area of confusion, the GCP began in its 2018 release to use the term "fossil CO_2", with the definition "emissions of CO_2 from oxidation of fossil fuels and decomposition of fossil carbonates" (Andrew, 2020a; Le Quéré et al., 2018). Some datasets exclude all emissions from decomposition of carbonates (e.g., IEA, EIA), so the term "fossil-fuel emissions" is still valid, but its use should be limited to datasets that do not include other emissions sources.

2.2. Refinements

Over the years refinements have been made to the methods, particularly in response to official queries as to why GCP's estimates differ from official estimates made in the most recent years, to which the answer was always simply that GCP's approach was approximate and aimed at using consistent methods for all countries (an aim now relaxed). Further refinements are a result of the identification of inaccurate emissions, for example the cement process emissions.

CDIAC-FF's data extended by growth rates derived from BP energy data effectively forms the starting point of GCP's dataset. Upon this foundation, we overwrite the emissions for reasons that fall into four main categories.

The first is where official estimates are available from developed countries. Here we assume that these are of higher quality because of the use of significantly more detailed data and information and the expertise developed over many years combined with external auditing via the UNFCCC.

The second case is where estimates from CDIAC-FF are in clear disagreement with those from other sources, including the IEA, which uses more detailed energy data and undertakes significantly more cross-checks than CDIAC-FF does.

The third is where final-year data are available that provide higher quality estimates than by using growth rates derived from BP.

The fourth is where CDIAC-FF's data contain implausible values (e.g., negatives) or rates of change (e.g., sudden, unexplainable discontinuities), or where checking against sources used by CDIAC-FF shows evidence of transcription errors.

The following sections describe specific cases where estimates from the underlying CDIAC-BP foundation are overwritten.

2.2.1. Annex-1 parties to the UNFCCC

Countries listed in Annex 1 of the UNFCCC are required to report detailed national greenhouse gas inventories (NGHGIs) annually to the UNFCCC in a standardised Excel format known as the Common Reporting Format. Andrew (2020a) summarises the history of this reporting requirement. With experience built up over many years of reporting and auditing, significantly greater detail, access to a wide range of source data, and use of multiple cross-validating methods, it is expected that these reports are significantly more accurate than the use of apparent consumption and globally constant emission factors, as with CDIAC-FF. These reports are disaggregated according to the IPCC 'sector' framework, which we then map to the components used by CDIAC-FF: solid, liquid, and gaseous fossil fuels, cement production, flaring, and bunkers. We add an 'other' category for fossil CO_2 emissions that do not fall into CDIAC-FF's categories, namely decomposition of carbonates in IPCC sector 2 (industrial processes and product use) apart from those in cement production (2A).

Most emissions can be mapped directly to CDIAC-FF's categories, but some in IPCC sector 2 (Industrial Processes and Product Use) are not detailed by the type of fuel that the fossil carbon originated in. We use a mapping method to estimate the share of fossil emissions in these smaller categories that came from each category of fossil fuel. Fossil-fuel emissions in the metals industry are assumed to come from solid fossil fuels, emissions in ammonia and urea production are assumed to derive entirely from gaseous fossil fuels, while emissions in the solvent, waste incineration and other combustion sectors are assumed to be entirely derived from liquid fuels. Emissions in the chemical industry and from fossil-fuel oxidation in other industrial processes are assumed equally divided between the three fuel types. Reported values are always used for national total emissions, and sums over categories always equal national totals, thus our assumptions only effect the distribution between the solid, liquid, and gaseous fuel categories.

The first deadline each year for submission of inventories to the UNFCCC by Annex 1 countries is 15 April, but revisions are made as required through the year. For the 2022 release of the GCB, we have used the Excel files from the UNFCCC downloaded on 14 June 2022.

Three countries submit full reports for more than one territory: Denmark, France, and the UK.

- For Denmark we use the 'DNM' reporting, which excludes Greenland and the Faroe Islands. The Executive Summary in Denmark's National Inventory Report refers only to emissions in Denmark (DNM) (DCE, 2021).
- For France we use the 'FRK' reporting, which includes only French overseas territories that are part of the EU. The French government's website on its national low-carbon strategy presents numbers that are consistent with FRK reporting, not FRA reporting (the latter is France's 'Convention' definition, and includes all overseas territories) (MTE, 2021). However, see also the later section 2.2.18 for further discussion on France.
- For the United Kingdom we use the 'GBK' reporting. While the UK's National Inventory Report clearly states that "The UK Government Carbon Budgets apply to the UK only, and exclude all emissions from the UK's Crown Dependencies and Overseas Territories" (p. 35, BEIS, 2021), the UK does not submit data to the UNFCCC based on this geographical definition, and the GBK geography is closest.

Many European countries are also required to report inventories to the European Commission, with the first deadline being 15 January each year (EEA, 2023; European Commission, 2020). Some of these countries make their submissions openly accessible, and these therefore represent official estimates updated to an additional year, three months before most countries UNFCCC submissions are available.

2.2.2. Norway

It has long been known in Norway that the reference approach (RA) using apparent consumption of energy products gives poor estimates for Norway's fossil-energy CO_2 emissions. Already over 20 years ago Norway's National Inventory Reports (NIRs) were highlighting this issue (SFT, 2002). A special report commissioned from the Norwegian Statistical Office on the subject demonstrated that the most significant reasons for the divergence between estimates using the reference approach and the sectoral approach were (Rypdal, 2001):

- Large crude oil and natural gas production and export
- Carbon content of exported crude oil is not monitored
- Large amounts of fossil energy used as feedstocks and reducing agents.

Later NIRs continued to put the problem down to uncertainties in production and export quantities along with large non-energy use of various fossil energies, with the 2010 report, for example, concluding "The end-user statistics used in the SA [sectoral approach] are considered reliable" and "These factors make the use of the RA inappropriate for Norway" (Klif, 2010, p. 129). Since at least 2014, the NIRs of Annex I parties have been reviewed annually by an expert review team (ERT; UNFCCC, no date), and Norway has reported every year in its NIR that the ERT has expressed concern about the magnitude of the difference between the RA and the SA (e.g., Miljødirektoratet, 2021).

Much of this deviation is a result of small errors that are amplified for a country that produces significant oil and gas but exports most of it: the error in the difference of production and exports is much higher in a relative sense than the error in either term alone. Norway serves here as an indication that the general use of the reference approach for any country with high exports of fossil fuels compared to consumption might lead to problems, and that official statistical effort is focussed more on energy used within the territory than energy sent out of it.

Since CDIAC-FF uses apparent consumption, equivalent to what the IPCC call the reference approach, CDIAC-FF's estimates for Norway show the expected considerable deviation from Norway's official estimates.

Since the GCP already uses official Norwegian estimates from 1990, derived from the national inventory reporting, it is emissions before 1990 that remain affected by this issue. We have therefore chosen to replace emissions before 1990 with estimates derived from official Norwegian sources (SSB, 2021, 2015, 2012). These series begin in 1973, which is when oil production began in Norway: at that time CDIAC-FF's estimates match Norway's own, and the problem with the apparent consumption approach only becomes significant as oil (and natural gas) production grew in subsequent years; CDIAC-FF's estimates before 1973 are therefore expected to be robust. Norway's official estimates from 1973 provide total fossil CO_2 emissions and disaggregation by sector. We use this sectoral information to map approximately to CDIAC-FF's components for continuity of the series.

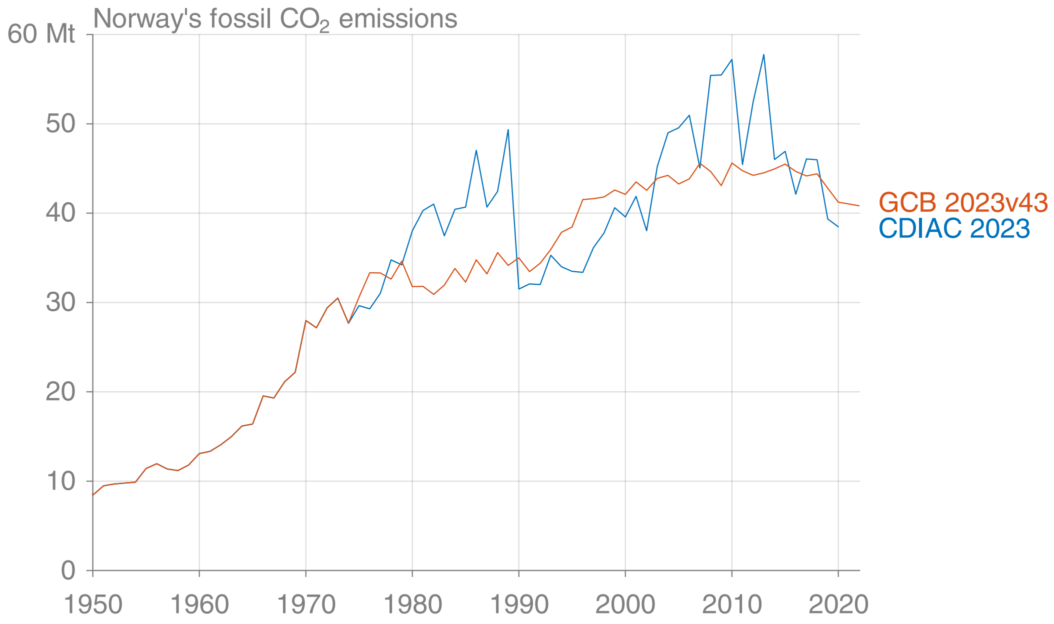

Figure 1: Comparison of estimated fossil CO_2 emissions for Norway from CDIAC-FF and GCP (this work).

2.2.3. China's emissions from lime production

While we use CDIAC-FF's estimates for China, temporally extended using data from BP for energy, these omit emissions from China's production of lime, which are significant, reported as being about 170 Mt CO_2 in 2018 by Cui et al. (2019). As with cement production, lime production involves the decomposition of carbonates, principally limestone. Official estimates of lime production are available in Chinese-language publications that are not readily available outside of China, so we collate a time series of estimates from various secondary sources (Shan et al., 2016; Liu and Wang, 1994; Cui et al., 2019) as well as data provided by Jos Olivier (pers. comm., June 2019), shown in Figure 2. More recently, Bing et al. (2023) have produced a new series using several multilinear regressions, resulting in much higher production before 1990, and this series is under consideration.

Olivier's data looks here like a complete series from 1960, but in fact is based on interpolation of few data points using proxies. The first data point directly sourced from elsewhere is for 1994 from China's first National Communication. From 1980 to 1993 this data point is extrapolated based on China's crude steel production, and from 1960 to 1979 the series is further extrapolated using the trend from about 35 other countries, mostly developed. It is difficult to know how reasonable these methods are, but there is divergence in the late 1980s from the data presented by Liu and Wang (1994). The earlier data presented by Liu and Wang (1994) are spurious since they state that the discontinuity in their reported numbers is due to incomplete coverage in the earlier part of the series.

Some interpolation is required over the years between the first National Communication and the earliest data from Shan et al. (2016). While Olivier's assumption of constant production over this period perhaps reflects the principle of Occam's Razor (simplest assumption that fits the available information), given the economic downturn in China in late 1990s (Keidel, 2007), it's perhaps more reasonable to assume that production continued to increase somewhat after 1994, before declining again during the economic downturn.

In recent years the USGS have been assuming in the absence of data that lime used in steel production is one-third of the total (pers. comm., USGS, May 2021), and the USGS estimates are therefore assumed to be of lower quality than those from Chinese sources using data from industry bodies. The divergence between the figure quoted for lime production in 2005 in China's second National Communication and those reported by Cui et al. (2019), Shan et al. (2016), and Olivier (2007) is not yet explained. China has not officially reported either lime production or emissions from lime production since the second National Communication, although it is included in aggregated totals in later communications to the UNFCCC.

The drop in the data reported by Liu and Wang (1994) between 1988 and 1990 is described as a result of an economic slowdown that was followed by an 'astonishing' recovery in 1991 and 1992. This dip in lime production therefore should be retained in the final series.

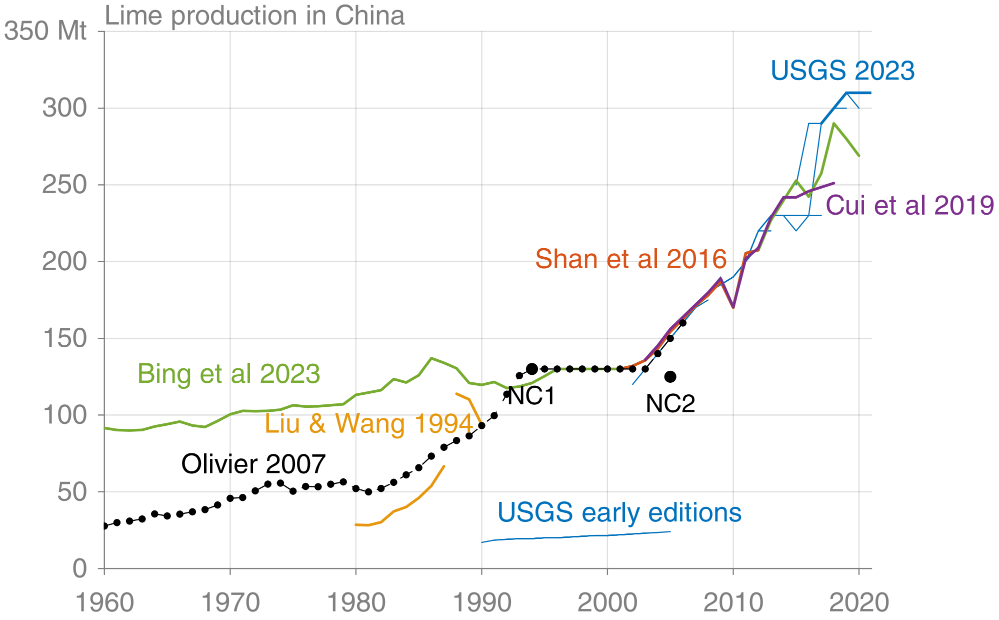

Figure 2: China's production of lime as reported by a range of sources. There is a gap in the data from Liu & Wang (purple line).

From these activity data we apply the emission factor used by Shan et al. (2016) (0.683 kg CO_2 / kg lime; sourced from the NDRC) for fossil CO_2 emissions from the decomposition of carbonates in the production of lime and arrive at the estimates shown in Figure 3. Uncertainty remains very high for estimates before 1988, and no estimates are available before 1960.

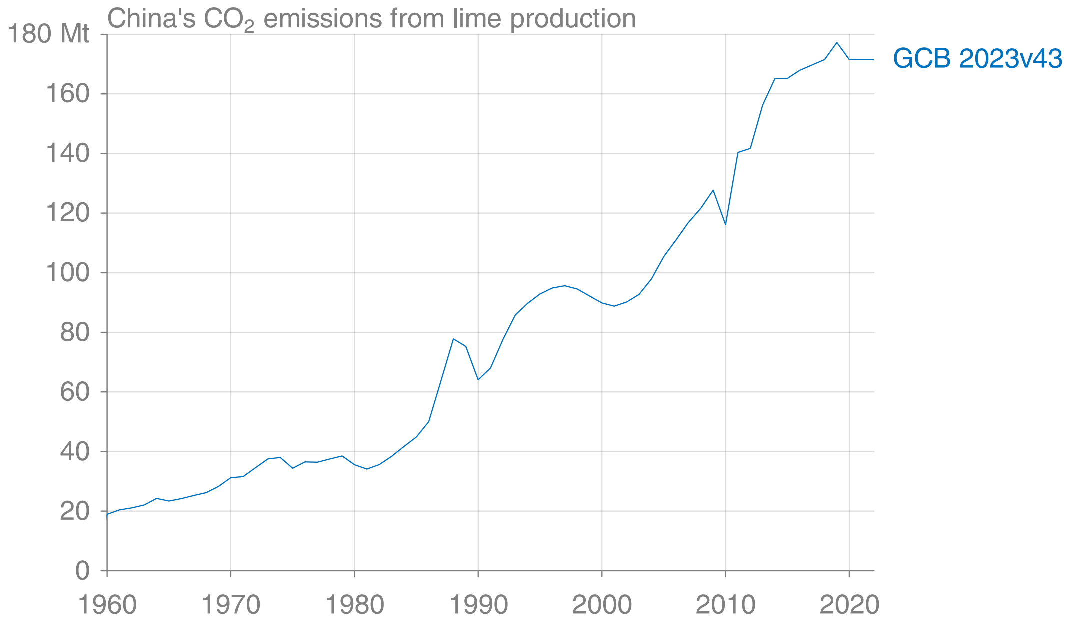

Figure 3: Estimated CO_2 emissions from China's lime production. No data are available before 1960.

2.2.4. Indonesia

CDIAC-FF's estimates for emissions from Indonesia's coal consumption exhibit significant interannual variation that is at odds with Indonesia's communications to the UNFCCC and estimates by both the IEA and BP. We presume this is a result of the apparent consumption approach amplifying reporting errors, and we therefore replace CDIAC-FF's coal emissions for Indonesia with our own estimates based on coal consumption data in energy units officially reported by the country (MEER, various years).

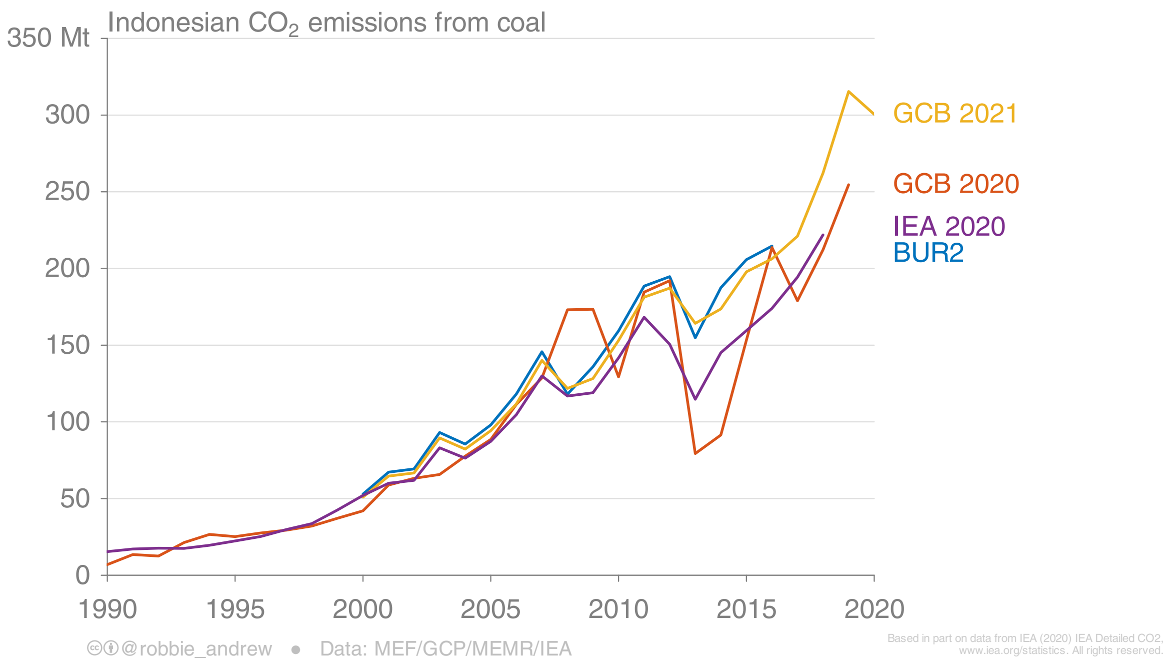

Figure 4: Comparison of Indonesia's CO_2 emissions from solid fuels reported to the UNFCCCC ("BUR2"), as estimated by IEA, and as estimated in GCB before and after using data directly from Indonesia.

2.2.5. United Kingdom

For the UK we extend emissions estimates officially reported to the UNFCCC with preliminary estimates made by the UK Department for Business, Energy & Industrial Strategy (BEIS, various years). Since BEIS' estimates cover a slightly smaller territory than those of the UNFCCC submission, we scale up a small amount to match the official UNFCCC estimates in overlapping years. This extension is only for the final year in the dataset.

The UK is the earliest territory with emissions in the dataset, but in the earliest period the original data were provided as averages of five-year periods. CDIAC-FF's implementation of this is simply to assign the same emissions to each year within each period, resulting in spikes in the derived first difference (rate of change). We return to the original coal production and trade data and set up a constrained optimisation problem that meets the constraints of the available data, while specifically avoiding artificial step changes in data by minimising the second difference of the signal. Effectively, we ensure that all information is used, while assuming step changes every five years are highly unlikely. The differences from the original series are minor, but this method avoids the discontinuities (Figure 5).

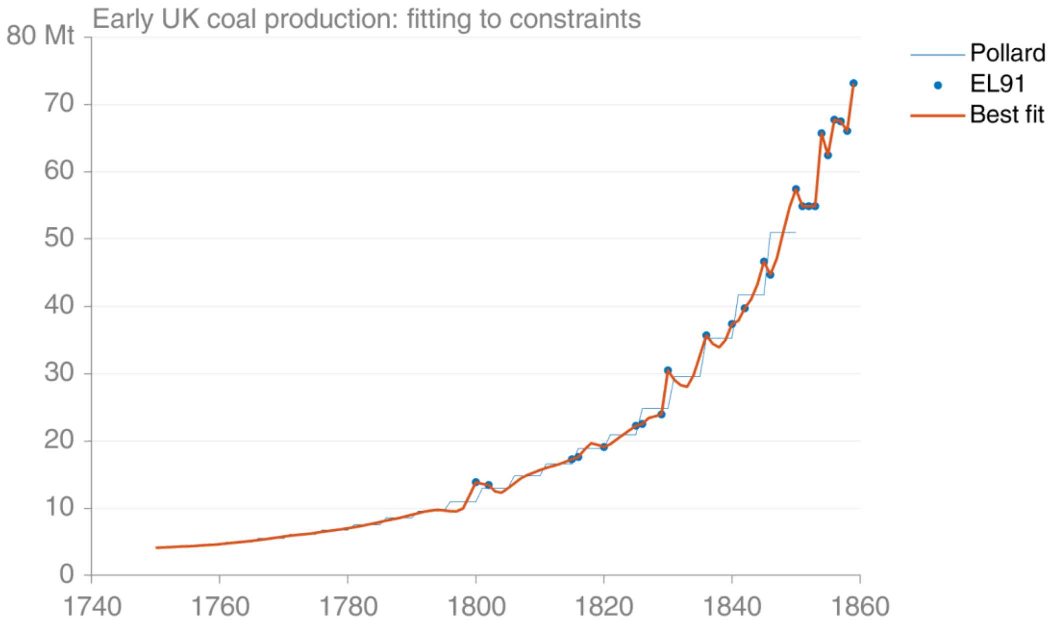

Figure 5: Coal production in the United Kingdom, showing the new series in red derived from available information. Pollard refers to Pollard (1980), while EL91 refers to Etemad and Luciani (1991).

2.2.6. Netherlands

The Netherlands recently began publishing quarterly estimates of territorial emissions (Andrew, 2021; CBS, 2020). We have used published total CO_2 emissions for the three years available, 2019–2022.

2.2.7. Iceland

CDIAC-FF's data for Iceland start in 1950, but the Icelandic statistics office publishes energy data starting in 1940 (Statistics Iceland, *Various years-a*). We use this to extend emissions estimates back another ten years (Figure 6). Note also that CDIAC-FF's estimates post 1990 differ significantly from those reported officially. This is believed to be mostly because Iceland imports significant quantities of carbon anodes for its aluminium industry, and these non-energy imports of goods derived from fossil fuels and oxidised as non-energy use are not captured by energy trade statistics.

Further, Iceland publishes low-lag monthly emissions estimates (Statistics Iceland, *various years-b*). These are estimated to align with national accounts data (i.e. based on the residency principle), but bridging 'sectors' are available to convert to territorial accounts. This provides a much better estimate of Iceland's emissions in the final year after official reporting to the UNFCCC, since Energy Institute data include bunker fuels, which are substantial for Iceland.

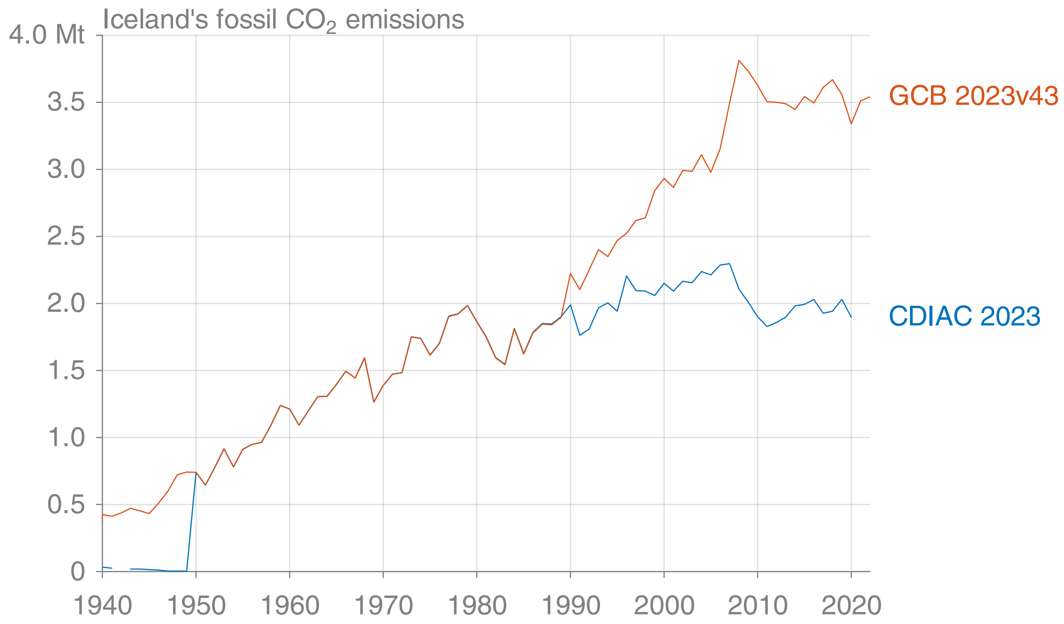

Figure 6: Comparison of Iceland's CO_2 emissions in CDIAC-FF and GCB (this work).

2.2.8. Liechtenstein

CDIAC-FF's data for Liechtenstein start in 1990, but the Liechtenstein statistics office publishes energy data starting in 1959 (Amt für Statistik, 2023). We use this to extend emissions estimates back another 31 years (Figure 7). However, the data are incomplete: while petrol is reported from 1959, diesel and heating oil data are absent before 1964, resulting in an artificial step in 1964.

Note also that official emissions statistics starting in 1990 are significantly higher than those estimated by CDIAC-FF using the Reference Approach.

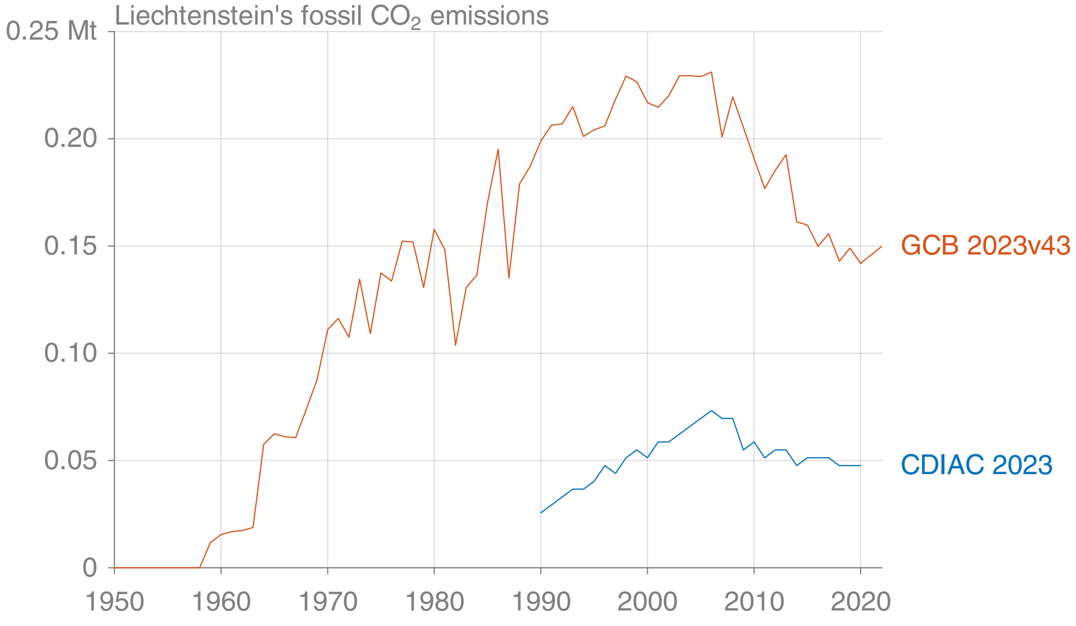

Figure 7: Comparison of Liechtenstein's CO_2 emissions in CDIAC-FF and GCB (this work).

2.2.9. Thailand

Thailand publishes monthly energy data and energy emissions with a lag of about six weeks (MoE, various years). The country's fourth biennial update report (BUR) states that the (more approximate) Reference Approach gives substantially higher emissions than the (more accurate) Sectoral Approach because of errors in the energy data for non-energy use of oil and production of synthetic fuels (MNRE, 2022). The emissions reported by the Ministry of Energy also match well the emissions reported in the fourth (most recent) BUR. Given that CDIAC-FF's approach is very similar to the reference approach, and that CDIAC-FF's emissions estimates for Thailand are higher than official estimates (Figure 8), particularly for oil, we choose to use the official estimates. We add emissions from use of urea using consumption data from the International Fertilizer Association (IFA, various years), and also emissions from cement production and flaring as for other countries, such that total emissions for Thailand in GCB are somewhat higher than those published by the Ministry of Energy.

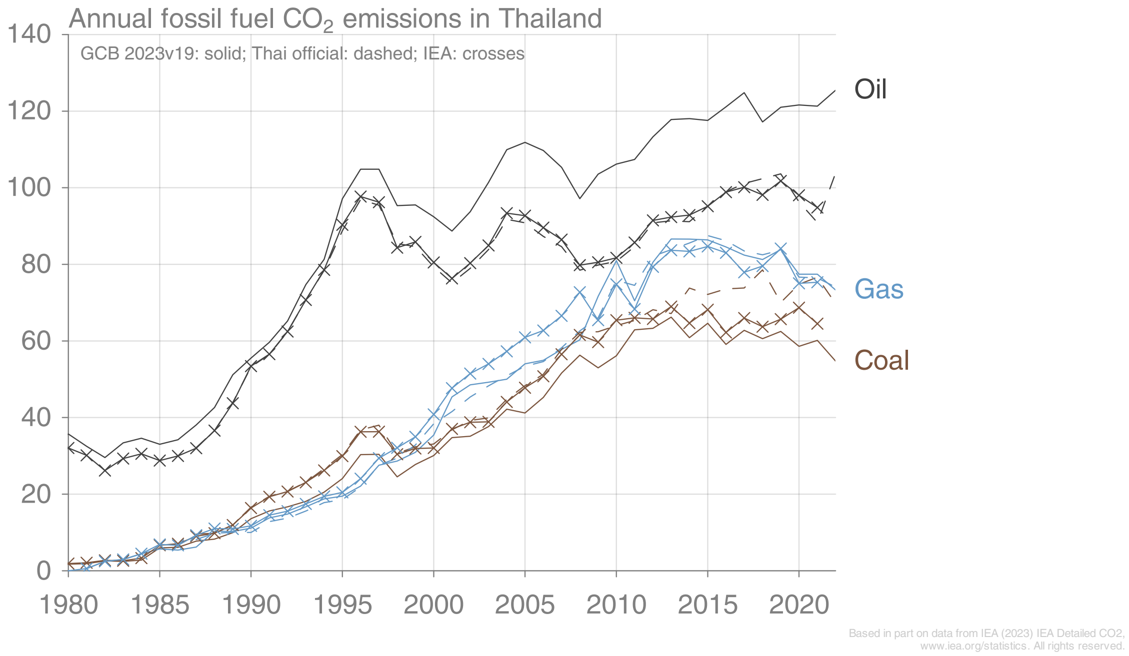

Figure 8: Thailand's emissions of CO_2 from fossil fuels, showing data from Thailand's Ministry of Energy, the IEA, and the previous (internal) edition of the GCB fossil CO_2 dataset.

2.2.10. United States of America

The Energy Information Administration (EIA) of the USA provides estimates of US CO_2 emissions from energy sources starting in 1973, and we use these semi-official estimates in preference to those from CDIAC-FF in this period (EIA, various years). However, we use these data to alter the shares of coal, oil, and gas emissions in the total, without changing the total, so that we retain total emissions from the official reporting to the UNFCCC from 1990. The changes from 1990 are minor and reflect small errors in the assumptions in our mapping of IPCC emissions categories to fuel types.

We further add emissions from US lime production before 1990, not included in CDIAC-FF's data. Lime production data from 1904 are taken from USGS (2017) and the constant emission factor of 0.75 tonnes CO_2 per tonne lime used in the US NGHGI is applied, with an assumed capture of 2.2% based on the reported capture for 1990 (EPA, 2021). This addition before 1990 reduces the 'other' emissions category discontinuity in 1990 somewhat, but not entirely.

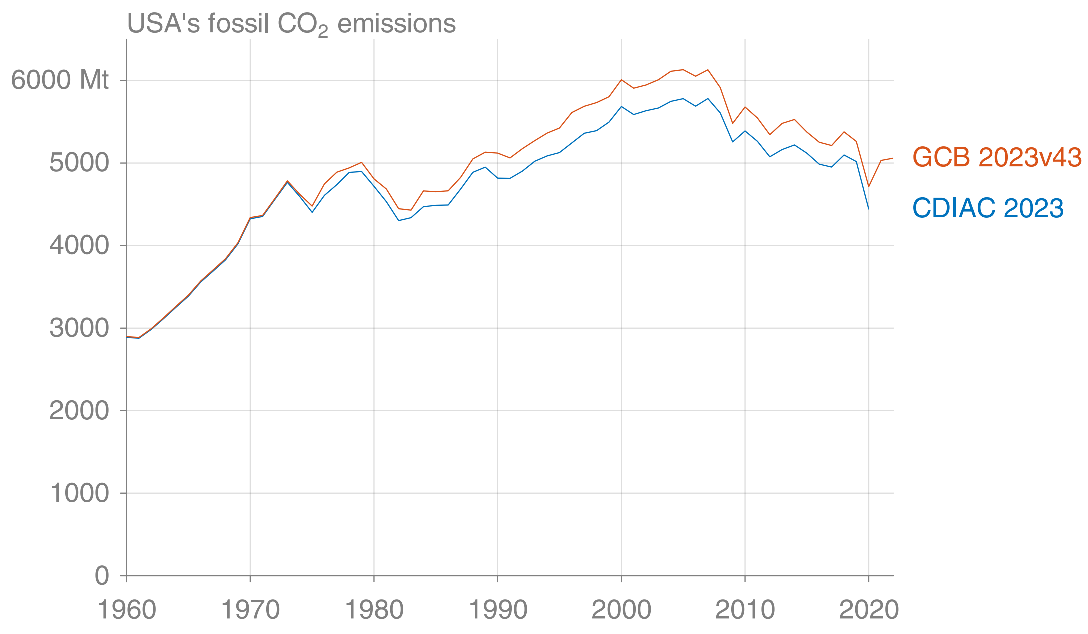

Figure 9: US fossil CO_2 emissions from CDIAC-FF and GCB (this work).

2.2.11. India

Andrew (2020b) introduced a new method for estimating fossil CO_2 emissions in India using monthly activity data (Andrew, 2022), and annual estimates derived from these were first incorporated into the GCP's fossil CO_2 dataset in 2020. Importantly, other datasets – including IEA, CDIAC-FF and BP – report emissions and energy for India's fiscal year, which ends in March, rather than the standard calendar year used for almost all other countries. The use of a monthly emissions dataset allows GCP to remove this source of error without resorting to simplistic weighting of fiscal year emissions. Further, Andrew (2020b) showed that the use of more detailed data produced slightly different trends (Figure 10). Use of this monthly dataset also means that the approximate approach using BP's energy data can be bypassed, since monthly estimates are available with a lag of only 2–3 months.

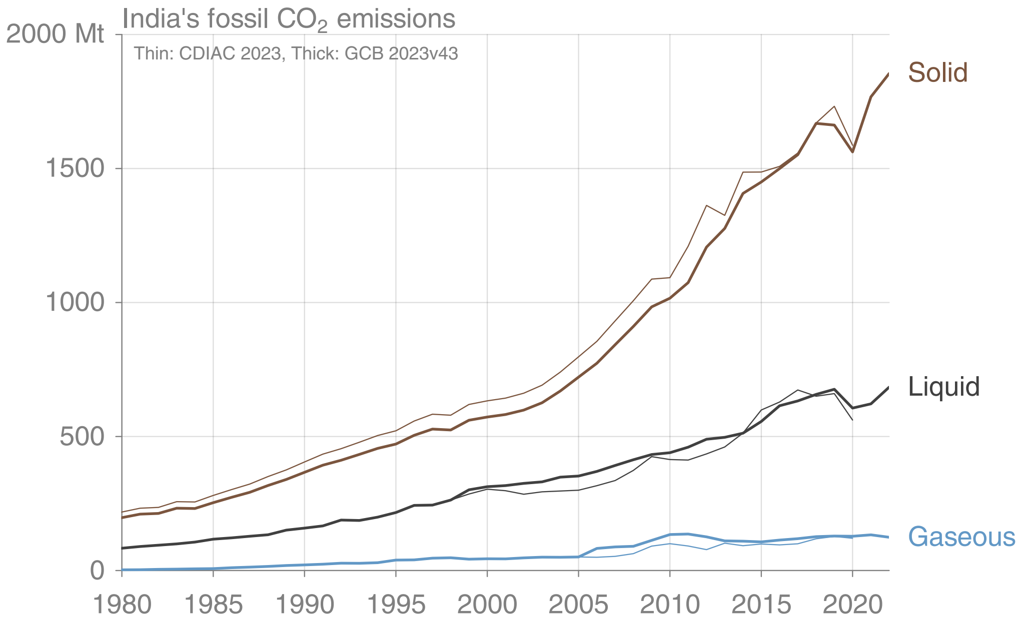

Figure 10: India's fossil CO_2 emissions from CDIAC-FF and GCB (this work), the latter updated from Andrew (2020b).

2.2.12. South Korea

While the Republic of Korea is not an Annex 1 party, it does publish a detailed national greenhouse gas inventory, following IPCC's guidelines (Ministry of Environment, 2021). Total fossil CO_2 emissions and CO_2 emissions from cement production over 1990–2019 are drawn from this series. However, the breakdown by fuel type used by the GCB is not provided in the inventory, so we derive these using detailed energy data from KEEI (2022) and apply the energy contents and emission factors used in the NGHGI to obtain annual fossil CO_2 emissions by fuel type through 2020. The sum of these is very close to the total in the NGHGI for fuel emissions, and we scale the bottom-up estimates the small amount necessary such that the sum equals the official total. This provides estimates for the period 1981–2021.

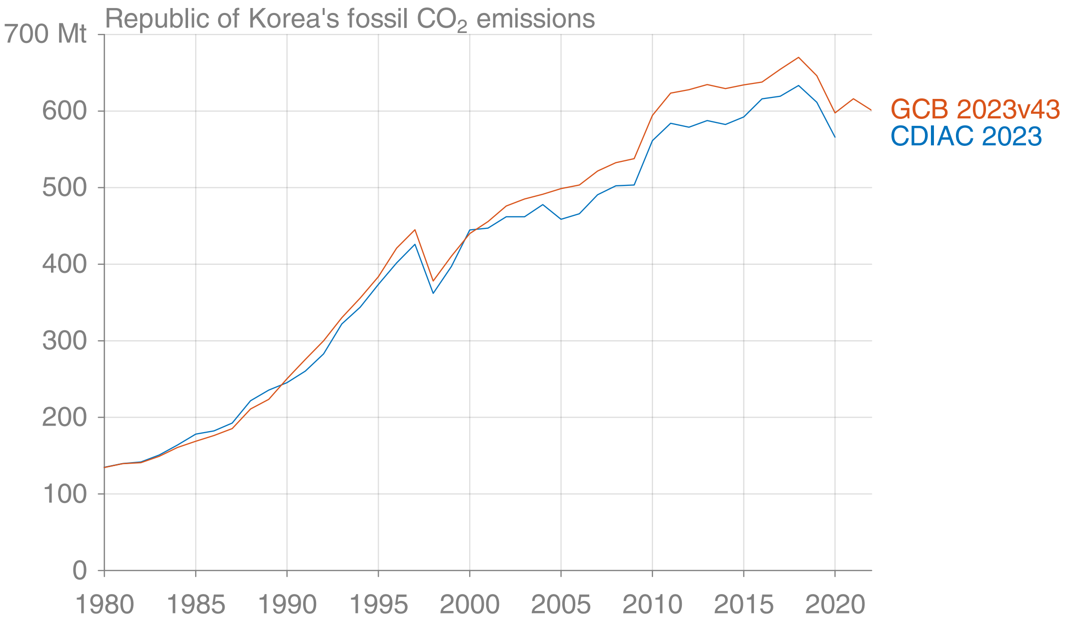

Figure 11: South Korea's fossil CO_2 emissions from CDIAC-FF and GCB (this work), the latter taken directly from official reporting for 1990–2018 and derived from detailed energy data 1981–2020.

2.2.13. Greenland

Denmark reports Greenland's emissions as part of Denmark's national greenhouse gas inventory in tables in Chapter 11 of the 2023 edition of this report (DCE, 2023). These have been assembled and we use the total fossil CO_2 emissions for 1990–2021 (Figure 12) and scale components to match the new totals.

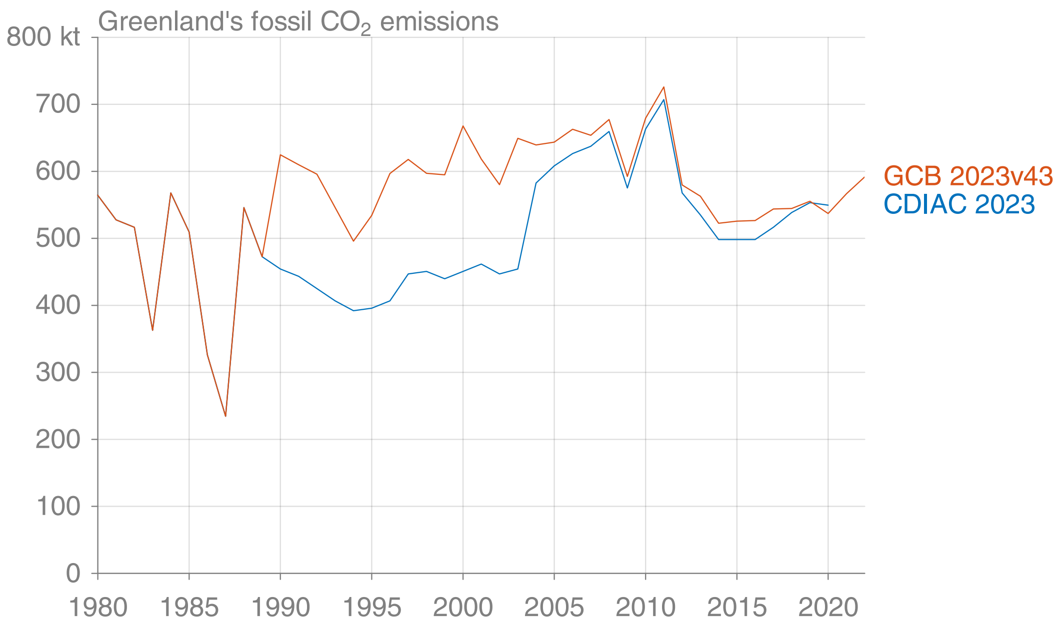

Figure 12: Greenland's fossil CO_2 emissions from CDIAC-FF and GCB (this work), the latter taken directly from official reporting.

2.2.14. Brazil

Brazil has been publishing detailed inventories for some years, and we use the inventory 1990–2016 from its fourth biennial update report (MFA and MSTI, 2020), which show somewhat higher emissions that those in CDIAC-FF.

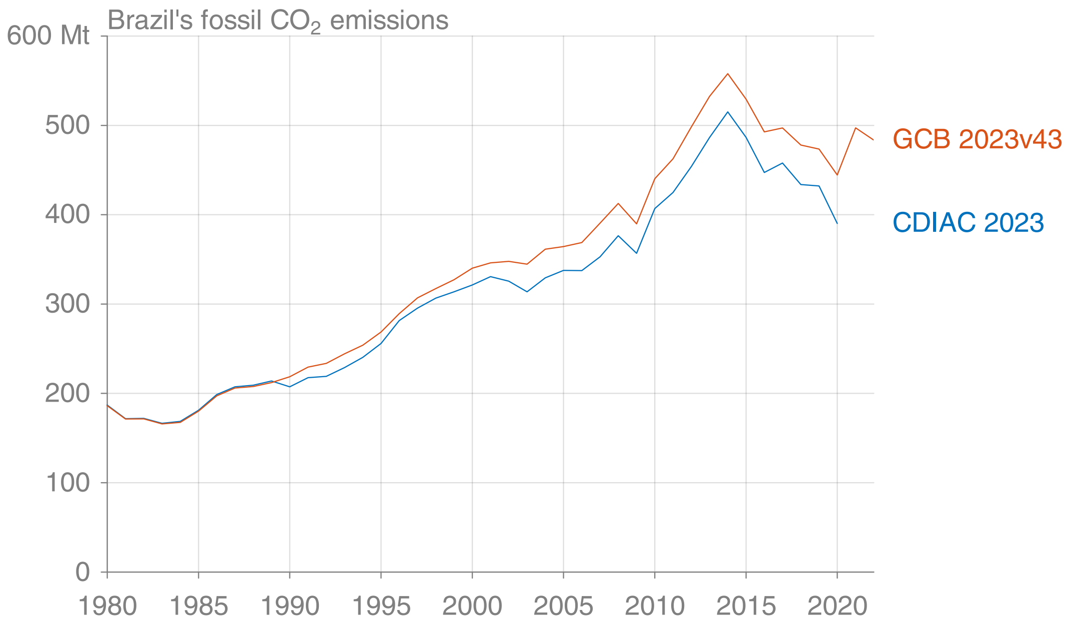

Figure 13: Comparison of Brazil's fossil CO_2 emissions in CDIAC-FF and GCB (this work), the latter taken directly from official reporting.

2.2.15. Taiwan

Taiwan is not a member of the United Nations and therefore does not report emissions to the UNFCCC. However, the country does publish detailed estimates of its emissions, and we use these (EPA, 2022) (Figure 14).

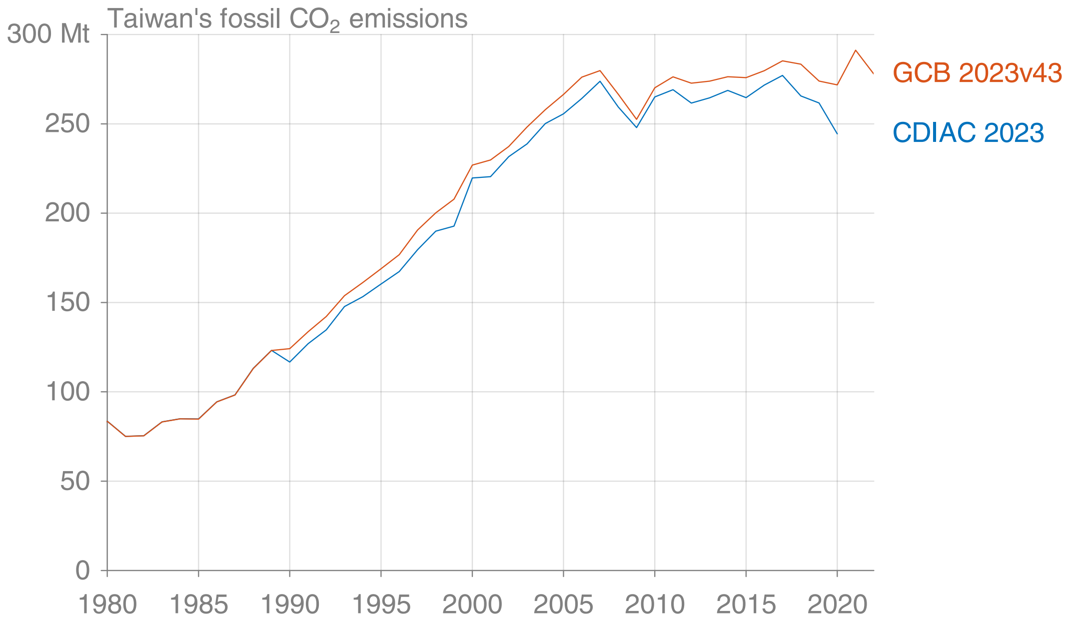

Figure 14: Taiwan's fossil CO_2 emissions from CDIAC-FF and GCB (this work), the latter directly from official reporting.

2.2.16. Germany

For Germany's emissions in 2022, we use the total reported by the Federal Environment Ministry (UBA, 2023), and scale the components the small amount necessary to match the total.

2.2.17. Australia

In 2020, BP's estimate for Australia's natural gas consumption in 2019 was very poor, and we chose to use data directly from Australia in preference (Friedlingstein et al., 2020), and we continue this. Australia reports to the UNFCCC for its fiscal year, July-June, rather than the internationally normal calendar year (DISER, 2021). For the period 1990–2022 we therefore use calendar-year fossil CO_2 emissions estimates derived from Australia's quarterly updates of its NGHGI (DISER, various years).

Neither trade data nor production prior to 1950 for oil and oil product were reported by the sources used by CDIAC-FF, such that CDIAC-FF reports emissions of zero in the liquid fuels category before 1950 (as do all other datasets currently). We make use of a new dataset of Australia's trade oil products in the period 1903–1960 compiled from official reports by Andrew (2023b). Given that there was no commercial crude oil production until the 1960s, use of trade data is sufficient to estimate consumption and therefore emissions, on the assumption that stock changes were minimal at that time.

CDIAC-FF's emissions from solid fuels in Australia show a marked discontinuity at 1990. Investigation shows that this is also present in the UN energy data, which show a sharp drop in coal consumption in the power sector. Other data sources show no such discontinuity, and it is likely that Australia has at some point submitted revised energy data to the UN, but only from 1990, such that the unrevised data before 1990 remain. We now use official Australian data on both hard and brown coal consumption starting in 1960 (DCCEEW, various years), with time-variant energy contents and IPCC default emission factors to estimate a time-series of emissions from coal for the period 1960-1989. To ensure continuity and allow for differences between the IPCC default emission factors and those used in Australia, we scale the estimates such that in 1990 they match those derived from the UNFCCC submission.

CDIAC-FF's estimates of Australia's emissions from solid fuels begin in 1860, but Australia was consuming coal well before that. We supplement CDIAC-FF's estimates using coal production data obtained from Mohr et al. (2015), which match exactly the sources used by CDIAC-FF for the period 1881-1915. For consistency, we estimate emissions directly from the coal production data and scale to match CDIAC-FF's estimate of emissions in 1900, which is equivalent to deriving an implied emission factor. The overwritten period spans 1805–1899.

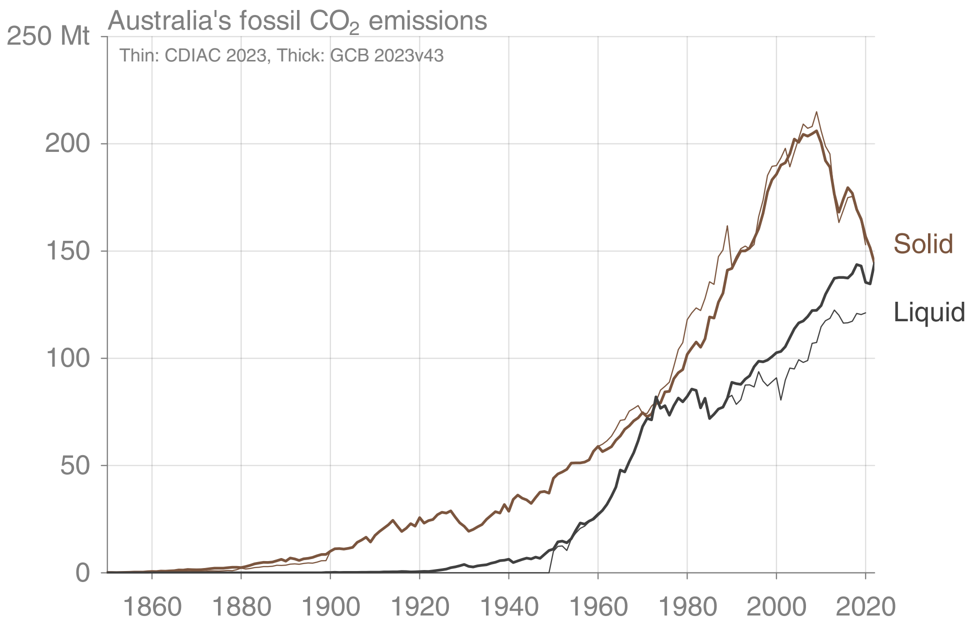

Figure 15: Australia's fossil CO_2 emissions from CDIAC-FF and GCB (this work).

2.2.18. France

France's official inventory submission to the UNFCCC is prepared by CITEPA, and while the UNFCCC only requires estimates starting in 1990, CITEPA publishes on its own website an inventory for Metropolitan France, starting in 1960, and France according to the Kyoto Protocol (KP) boundaries, starting in 1990 (CITEPA, various years).

Metropolitan France is effectively France geographically within Europe, which includes Corsica, but excludes both EU overseas territories (Guadeloupe, Martinique, Réunion, Guyana, Mayotte, Saint-Martin) and non-EU overseas territories (New Caledonia, Saint-Pierre et Miquelon, Wallis and Futuna, Saint Barthélemy, French Polynesia, and the French Antarctic territory). The KP boundaries for France include the EU overseas territories but not the non-EU overseas territories.

Monaco's energy data have long been reported in combination with those of France to the UN and other international organisations, and for this reason the emissions estimated for France by CDIAC-FF include Monaco. However, CITEPA's territorial definitions, which are very clear, do not include Monaco. Monaco reports separately to the UNFCCC as an Annex-1 party, but these data begin only in 1990, meaning that no estimates are available before 1990. Therefore, we maintain the traditional grouping of combining Monaco and France. While no estimates are available before 1990, we add Monaco's official emissions estimates from their NGHGI to France's from 1990. These amount to only 0.1% of France's total fossil CO_2 emissions.

In international energy reporting prior to 2011, France included New Caledonia, French Polynesia, Saint Barthélemy, Saint Martin, Saint Pierre and Miquelon, and Wallis and Futuna (IEA, 2019). CDIAC-FF's emissions estimates for these territories therefore disappear from 2011 onwards.

For Guadeloupe, Martinique, Réunion, Guyana, and Mayotte after 2010 we use the difference between the totals in CITEPA's two territorial definitions (i.e., KP less Metropolitan France) combined with the shares in 2010 in CDIAC-FF's data, resulting in approximate estimates beyond 2010 for these territories.

NOTE: In this 2023 release, the French overseas territories are not represented correctly. France no longer reports these territories separately to the UN, and CDIAC-FF therefore reports their emissions as zero and includes them in with France. We will be investigating solutions to this issue for the next release.

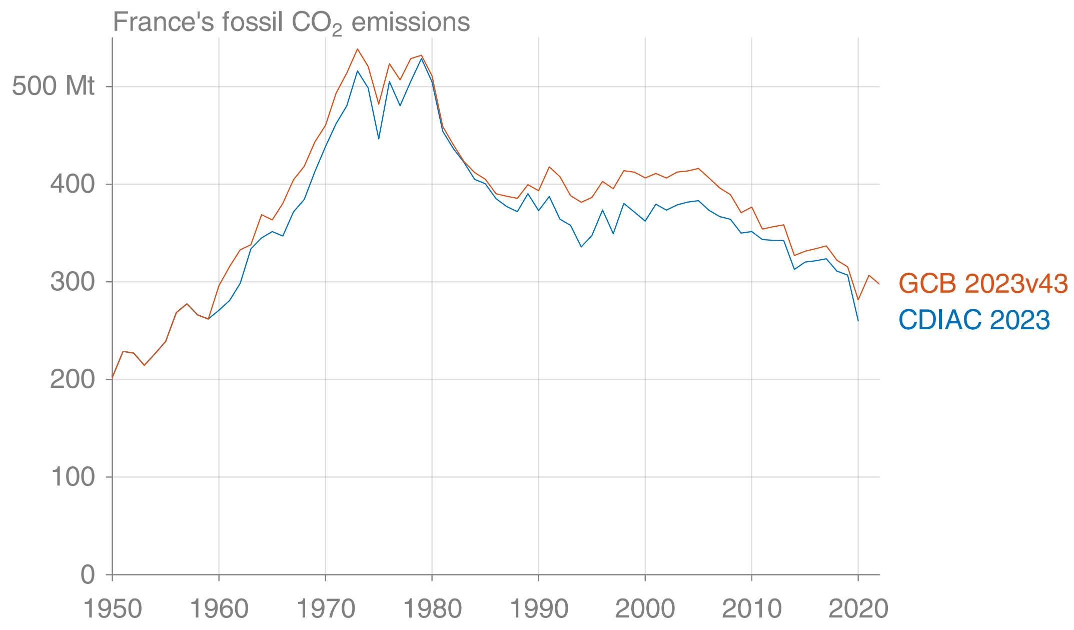

Figure 16: Comparison of France's fossil CO2 emissions reported by CDIAC-FF and GCB (this work).

2.2.19. Finland

Finland's statistics office publishes preliminary estimates of the previous year's territorial emissions (Statistics Finland, 2023), and we have used these to extend the emissions officially reported to the UNFCCC/EC.

2.2.20. Sweden

Sweden's statistics office (SCB) publishes preliminary estimates of the previous year's territorial emissions (Statistics Sweden, 2023), and we have used these to extend the emissions officially reported to the UNFCCC/EC. Final estimates from SCB are usually not available until December.

2.2.21. DR Congo

In CDIAC-FF's estimates, emissions from coal in the DR Congo drop to zero in 1991. Neither the UN nor IEA energy data have any coal data after 1990. The EIA does have data, although much lower than before 1990 (EIA, *no date*). The explanation is that there was considerable upheaval in the country late in 1991, which lasted for several years (Wikipedia, 2023). It appears this has set industry and mining back in the country. There are no coal-fired power stations in the country, according to

Global Energy Monitor (2023), and the steel mill is still largely dormant. We now use the coal-energy data from the EIA post 1990 to estimate emissions, but they remain much lower than they were in the 1980s.

2.2.22. New Caledonia

New Caledonia publishes annual energy consumption data with a relatively low lag (DIMENC, *various years*). These agree well with CDIAC-FF's estimates, but the final two years diverge from estimates derived using the energy growth rates provided by EI for the region to which New Caledonia is allocated (Figure 17).

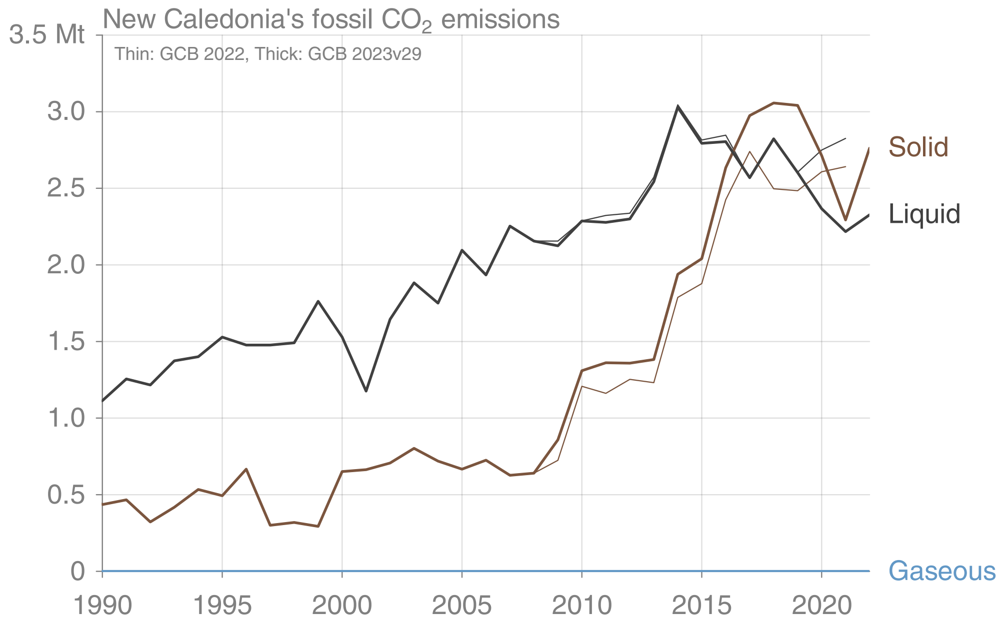

Figure 17: Comparison of New Caledonia's fossil CO_2 emissions reported in GCB 2022 and this release.

2.2.23. Latin America

CDIAC-FF's estimates for years prior to 1950 come directly from Andres et al. (1999), who in turn used production data from Etemad and Luciani (1991) and trade data from Mitchell (1993). However, for Latin America, those sources only provided production data for Argentina, Brazil, Chile, Colombia, Mexico, Peru and Venezuela, and trade data for Argentina and Brazil. CDIAC-FF thereby lacks estimates for most countries in Latin America prior to 1950, and for some countries the lack of trade data is significant, given the high reliance on imported coal (Yáñez et al., 2013).

Given these gaps, we make use of the data collated by Yáñez et al. (2013) on annual apparent consumption of coal by 20 Latin American countries from 1841. While records of coal trade are not available for most of the countries in the region, Yáñez et al. (2013) argue that the great majority of imported coal came from Britain, Germany, and the US, and that detailed records are available of exports by destination from three countries. Given that exports from Latin American countries (apart from bunker sales) were very low, using any production combined with imports in most cases gives reasonable estimates of apparent consumption. Where export data are available these were also included. Note that the consumption estimates explicitly do not subtract sales of bunker fuels, which is currently consistent with the rest of the GCB dataset prior to 1950.

While Yáñez et al. (2013) provide estimates through the year 2000, we overwrite CDIAC-FF's estimates only through 1940 (Argentina and Brazil), 1950 (Bolivia, Chile, Colombia, Cuba, Dominican Republic, Guatemala, Haiti, Honduras, Nicaragua, Panama, Peru, Uruguay, and Venezuela), and 1960 (Ecuador, El Salvador, and Paraguay). These end-years have been chosen based on the matches between series as well as the presence/absence of estimates in CDIAC-FF in the 1950s.

For consistency, we apply the same emission factors used by Andres et al. (1999) for hard coal to the apparent consumption in tonnes.

During our analysis we noticed that CDIAC-FF's estimates have apparently omitted information provided by Etemad and Luciani (1991) on coal production in Brazil before 1940 and Colombia before 1950.

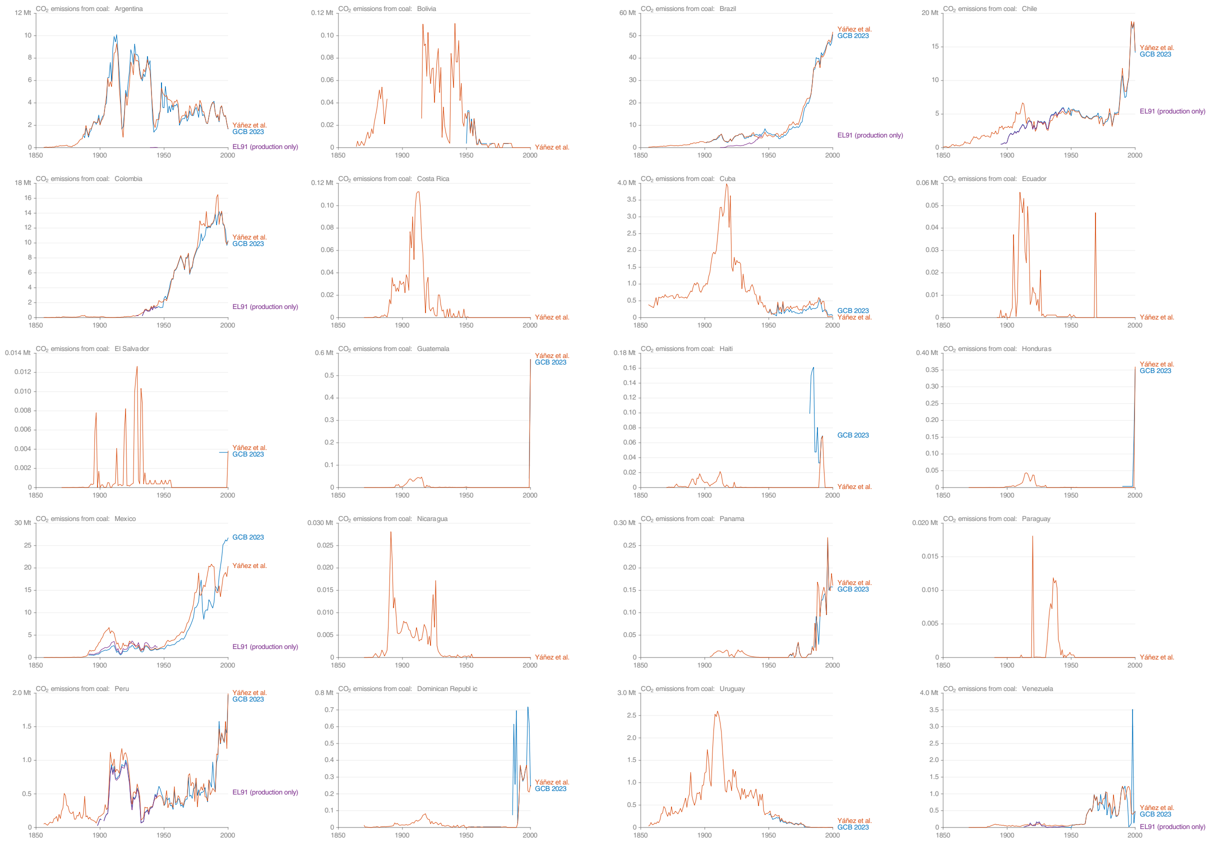

Figure 18: Comparing CO_2 emissions from consumption of coal for Latin American countries as estimated from (Yáñez et al., 2013) (red) compared with the previous version of the GCB (blue), and emissions estimated for coal production only from (Etemad and Luciani, 1991) where available. Note: while this figure is far too small to see clearly at print scale, the on-screen version permits full zooming into details in your PDF reader.

2.2.24. Cement process emissions

Given the demonstrated problems with CDIAC-FF's long-standing method for estimating emissions from cement production (e.g., Ke et al., 2013), we use an annual update of the estimates produced by Andrew (2019), the most recent edition updated by (Andrew, 2023a). This latest update includes estimates of emissions from cement production in the United States from 1880 and uses country-specific data and methods for a number of countries that are not Annex-1 parties to the UNFCCC. The 2018 release of the Global Carbon Budget (Le Quéré et al., 2018) was the first to replace CDIAC-FF's cement estimates with those of Andrew (2018). In its 2020 release CDIAC-FF revised its approach, making use of additional data sources from 1990 (Gilfillan and Marland, 2021).

2.2.25. International transportation (bunkers)

CDIAC-FF provides emissions from bunker fuels allocated to each country, but excluded from country totals, per convention. We use the energy data from the UN to derive separately emissions from international aviation (our code XIA) and international shipping (code XIS), and also break these down by fuel category in the case of shipping. While almost all shipping since 1950 has been fuelled by oil products, in the 1950s there was still some coal used, and in recent years the use of natural gas has begun.

2.2.26. Other corrections to CDIAC-FF's data

Following Andrew (2020a), the GCP makes corrections to emissions in the Soviet Union in the 1940s and Curacao in the 1930s and 1940s. Cumulatively these corrections amount to over 1.4 Gt CO_2 (Friedlingstein et al., 2020).

CDIAC-FF's estimates prior to 1950 are taken from Andres et al. (1999), who in turn used energy production data from Etemad and Luciani (1991). The earliest energy data reported by Etemad and Luciani (1991) is for the UK, but there is a minor error in that the original source, Pollard (1980), reports 'quinquennial' average coal production in Great Britain, but the first period is actually six years, 1750-1755. This is misreported by Etemad and Luciani (1991) as 1751–1755, which propagated via Andres et al. (1999) to CDIAC-FF's estimates for many years. The GCP corrects this minor error, resulting in a dataset beginning in 1750 rather than 1751.

The GCP's dataset also addresses all negative emissions in CDIAC-FF's data. These negative values arise because of CDIAC-FF's apparent consumption approach and errors in the data, such that, for example, exports can be greater than the sum of production, imports, and drawdowns from stocks. The largest of these negatives are quite early in the series, 1950 and earlier, when the energy data are of lower quality. For example, Iran's emissions in 1950 are calculated to be negative, but this appears to be because 1950 calendar-year production and crude oil export data are combined with Iranian year (year ended March 1950) data on exports of petroleum products at a time of high volatility. Further, the shifting territorial boundaries in the early 20th century, particularly in Europe, mean that data on production sometimes do not align with data on trade.

CDIAC-FF's data show a single year of non-zero oil emissions in Puerto Rico in 1920, the amount of which is about 0.1% of US oil emissions in that year. Looking at the original sources, this appears to have been a transcription error, so we have forced this data point to zero.

2.2.27. Emissions from international transport since 2020

Because of the exceptional circumstances since 2020 with the global pandemic, use of oil for international transportation (both aviation and shipping) has been affected differently to use for domestic transportation. This category, known as emissions from bunker fuels, is generally not well known in the final year or two of the dataset and has therefore historically been extrapolated from the final reported data year. However, since 2020 this extrapolation is likely to be erroneous, and an alternative approach has been introduced.

The OECD began publishing estimates of emissions from international aviation in 2022 (Clarke et al., 2022). Since these are not entirely consistent with the previous series from CDIAC-FF, we use growth rates from the OECD data to extrapolate CDIAC-FF's estimates.

Using global ship location data, Marine Benchmark reported that CO_2 emissions from international shipping declined by 1% in 2020 (Marine Benchmark, pers. comm., 22 July 2021). This is consistent with a report by EnerData that energy consumption in international shipping from the G20 group of countries was down by 0.7% in 2020 (EnerData, 2021). While Marine Benchmark continues to produce these estimates, they are no longer made public, so we have introduced an interim method based on linear regression of Marine Benchmark's monthly emissions against monthly freight data derived from AIS data by the IMF and published on the UN COMTRADE platform (Cerdeiro et al., 2020). The OECD has begun work on emissions from shipping, and if they derive emissions from international shipping as part of their work, then we will switch to that as a preferred data source.

Given that making these changes to international shipping changes the global total oil, we maintain expected global total oil emissions in final years by constraining the growth rates to those derived from EIA data (EIA, various years). To meet this global constraint, we make a small adjustment to domestic emissions from oil in those countries for which we have relied on EI/BP growth rates (i.e., those for which we do not have more reliable data sources).

2.2.28. Flaring

For CO_2 emissions from flared natural gas GCP starts CDIAC-FF, which derives its estimates from national reporting to the UN. However, CDIAC-FF's "flaring" also includes vented CO2 and vented CH4. As described above, we overwrite data for some countries with official estimates. Estimates derived using newer, independent, satellite-based methods show some deviation at global level (Figure 19) and particularly at national level. We use data from the Global Gas Flaring Reduction Partnership (GGFR, various years; Elvidge et al., 2009) for non-Annex I countries from 1994 in this edition of the GCB, and will investigate further whether the GGFR data suggest that any Annex I countries' reporting may be incorrect. The GGFR data are available for 1994-2010 and 2012-2022, with the year 2011 being filled with simple linear interpolation. The use of GGFR data means that vented CO_2 is omitted, which we will have to investigate further. For example, in the case of New Zealand, officially reported fugitive CO_2 emissions are higher than those from GGFR, presumably because the official numbers include vented CO_2.

There remain significant discontinuities in important countries due to poor data coverage, and we will continue to investigate solutions to these. Examples include zero emissions in the UK in 1988-1989, China in 1985-93, Nigeria 1989-1993, and substantial jumps in 1990 where Annex-1 countries start their reporting to the UNFCCC.

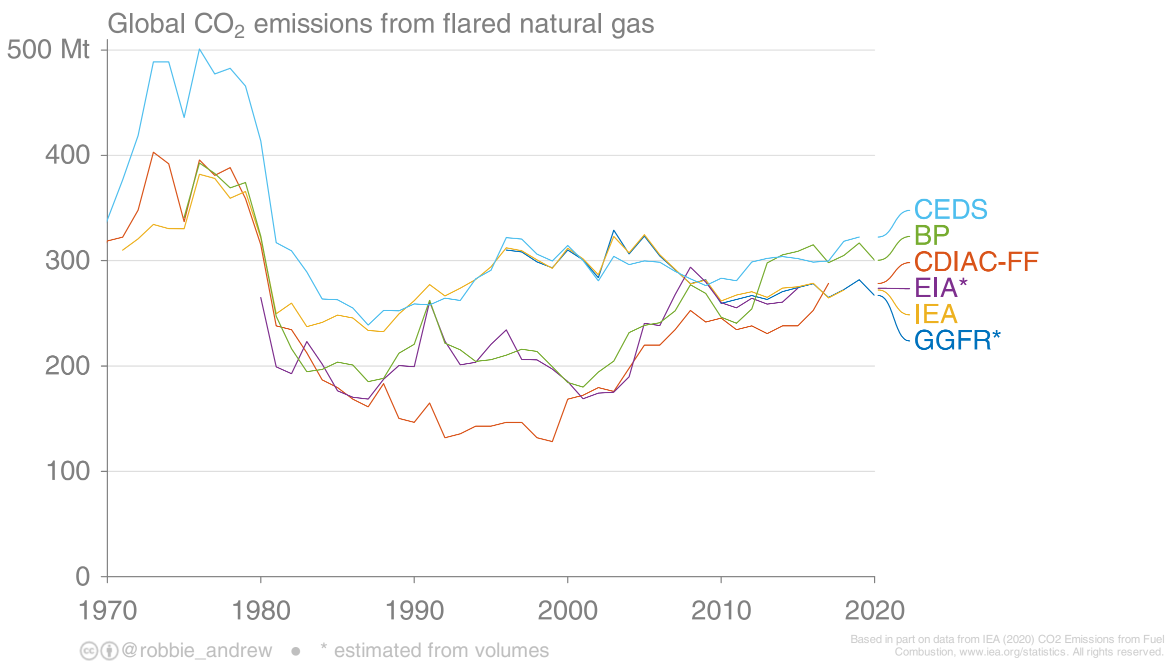

Figure 19: Comparison of estimates of annual global CO_2 emissions from flared natural gas from different sources.

2.2.29. Extrapolation in final years

Our extrapolation of observations to the final years (Y-1 for Annex 1 countries and both Y-2 and Y-1 for others) is largely based on energy growth rates derived from BP (now Energy Institute) data. However, BP's oil data include supply to international bunkers, and particularly in 2020, when international transport was affected quite differently to other uses of oil, this potentially gives biased estimates (e.g., see section 2.2.7 on Iceland). Further, BP provides country-level data only for larger countries, with many being grouped into 'rest-of' regions, the growth rates for which are applied by GCP to all countries within the respective groups.

The Joint Organisation Data Initiative (JODI) dataset collates monthly, high-level data for oil and natural gas for a large number of countries (JODI, *no date*). The oil dataset makes no distinction of biofuels, making it unsuitable for many countries for estimating fossil CO2 emissions, but might be useful for some countries with known low penetration of biofuels. However, information from this dataset could be used for countries that fall into BP's 'rest-of' regions, rather than using the same growth rates for all countries within the region. The use of JODI gas data was introduced in our 2023 release, providing both (1) earlier inclusion of final-year estimates than EI's dataset provides, and (2) any subsequent revisions, since EI's data is only published annually.

The UN energy dataset used by CDIAC-FF includes later data for developed countries. CDIAC-FF only uses the data through the final year in common across all countries, which means it excludes this extra year of data for the developed countries. We have now implemented a method where we estimate emissions from the UN energy data directly, and when our estimates compare very closely with those reported by CDIAC-FF in previous years, we add the additional year to GCB instead of using EI data for that year. For example, in 2023 UN energy data ran through 2021 for developed countries and 2020 for all others, so that CDIAC-FF 2023 edition only ran through 2020. We then could add 2021 data for those countries where UN included these.

2.3. Per capita series

There is frequent demand for data on emissions per capita, partly reflecting the effort required to align emissions data with population data. The GCP uses UN data available from 1950 (UN, various years), and Maddison (2010) before that. The only exceptions to this currently are Finland, Iceland, Sweden, and Norway, where official population estimates are used from 1750. UN population data for the most recent 1–2 years of the dataset are projections rather than observations, but indeed even recent 'observations' have often been interpolated by the UN from infrequent censuses. Users of the per capita data series should note that smaller countries with lower quality data can be highlighted when looking at per capita emissions, and caution should always be used when interpreting the emissions trajectories of such countries.

2.4. Continuous country definitions

While CDIAC-FF's emissions estimates from 1950 directly reflect the country boundaries of the underlying reporting by the UN, the GCP chooses to maintain unbroken time series for countries that currently exist. For example, there was no nation Russia for many decades of the 20th Century, but we disaggregate this out of the Soviet Union's emissions estimates given the clear utility of having long continuous data series.

In general, our approach is very simple, with the shares of emissions in each category in the first year after new countries split out of larger ones used for all years before the split. For example, Czech emissions from solid fuels were 81% of the total of Czech and Slovak emissions from solid fuels in 1992, so that we derive Czech emissions from solid fuels in 1991 as 81% of the Czechoslovakian value.

The transition period between the Soviet Union and the new countries that were formerly Soviet states was dramatic, with very significant shifts in the economies and emissions before and after the dissolution of the Soviet Union at the end of 1991, and effects varied across countries. It is therefore important to represent this transition well. BP's Statistical Review of World Energy (BP, 2021) has data for former Soviet states from 1985, based on the limited available pre-dissolution data by republic (pers. comm., BP, April 2019). We disaggregate years before 1985 using the shares in 1985.

Despite these efforts to disaggregate these countries carefully, emissions estimates before 1992 necessarily have higher uncertainty, and before 1985 must be considered tentative.

Countries that are disaggregated are: Czechoslovakia, USSR, Yugoslavia, East and West Pakistan, Rhodesia-Nyasaland, United Korea, Federation of Malaya-Singapore, Sudan, Netherland Antilles, French Equatorial Africa, and French West Africa.

Also for reasons of continuity, we aggregate countries that are now united: East and West Germany are combined into Germany for a continuous series; Zanzibar and Tanganyika are combined into Tanzania; North and South Yemen are combined into Yemen; North and South Vietnam are combined into Vietnam; Peninsular Malaysia, Sabah, and Sarawak are combined into Malaysia.

Note that Western Sahara's energy data are reported by Morocco, and its emissions are included in Morocco's data in GCB. Similarly, Monaco's emissions are included in France's data, and The Holy See (Vatican City) are included in Italy.

2.5. Source documentation

We continue to improve the tracking of sources in each data point through the entire workflow. Internally this is stored as binary values to allow compact storage of multiple tags per data cell, while for publication this information is translated to text in the same file format as the data file.

3. Revisions over time

The refinements introduced to the methodology over time have obviously led to changes in the level of emissions (Figure 20). This section briefly summarises some of the major changes seen between versions of the dataset.

The 2016 version (green line, with data ending in 2015) stands out with higher emissions through the mid-2000s. At the time this version was constructed China had released the results of its third Economic Census (3EC), which showed significantly higher coal consumption than previous releases. Analysis of CDIAC-FF's estimates showed that the 3EC results had only propagated through the UN energy data CDIAC-FF used from 2010 onwards, but Korsbakken et al. (2016) showed that China had revised its coal consumption upwards from 2000, and BP's data for China's coal reflected this, showing higher consumption from about 2000. Based on this we chose for the 2016 version of GCB to overwrite emissions for China for all three fuel categories using energy data reported by BP. The following year, with the 2017 version, CDIAC-FF's emissions estimates showed revisions for emissions from coal in China up across all years since 2000, so we switched back again to CDIAC-FF as our data source.

In its 2018 edition, the GCP replaced CDIAC-FF's estimates of cement process emissions with those of Andrew (2018), leading to a reduction in global emissions of about 0.5 Gt in recent years.

In the 2019 edition GCP recalculated global emissions as the sum of national emissions and international bunkers. This resulted in an increase in global emissions before 2012 and a decline after 2012 compared to the global emissions reported by CDIAC-FF.

In the 2021 edition, the addition of emissions from lime production in China added about 170 Mt CO_2 in recent years.

In the 2022 edition, CDIAC-FF's upwards revision of China's emissions from coal during 1999-2003 added 200–280 Mt CO_2 per year in that period.

In the 2023 edition there are many changes, the largest of which are in 2020-21 because of the replacement of 2020 estimates from approximate energy growth rates with estimates from CDIAC-FF.

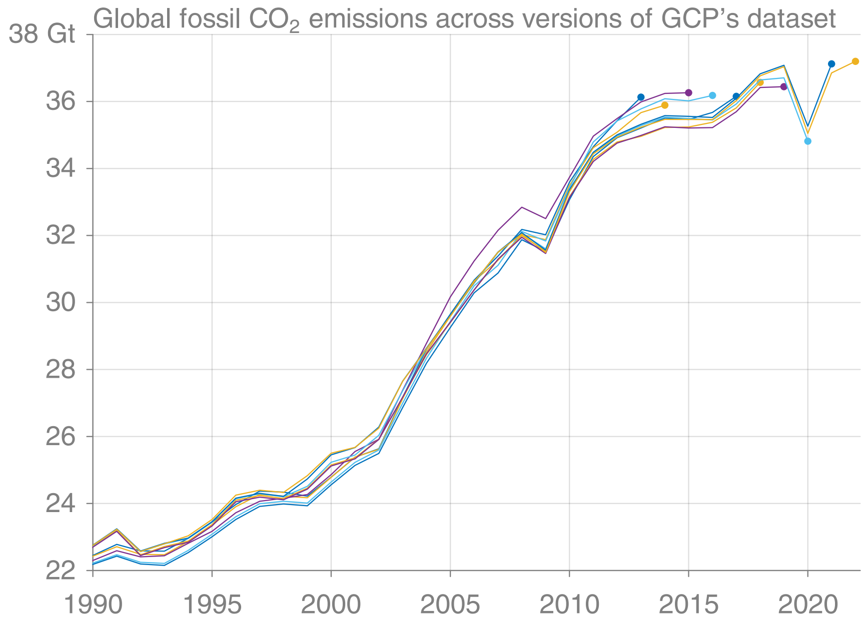

Figure 20: Comparison of global fossil CO_2 emissions from different versions of the GCB dataset. The final data point of each version is always the year before the version number, e.g., the 2021 edition has data through the year 2020 (Y-1).

4. Further Research

4.1. Extrapolation in final years

For countries that report to Eurostat, CICERO's other work towards generating monthly emissions estimates from Eurostat's energy data (Andrew, 2021) could be used to provide estimates of emissions in Y-1 that respect the definition of territorial emissions, excluding bunker fuels. This is a work in progress, as the underlying data from Eurostat are of highly variable quality.

4.2. Clear geographies

Historically GCP's fossil CO_2 dataset has provided no additional information about the geographies of countries included beyond a name and a three-letter ISO code. Given that these are imprecise, and that the exact geographies differ between data sources used, more careful tracking of geographies is something we intend to look at in future. This would require clear definitions of geographies for data from each source dataset and tracking via the source information. It may transpire, for example, that cement emissions for one country have a different geographical boundary to the energy emissions for the same country, because of the different data sources used. Most important, however, is to address the lack of clarity about what a name like 'France' means (see section 2.2.18), whether it includes Monaco, French territories within Europe, overseas territories and regions, or indeed French territory in Antarctica. It is expected that this will be demanding work. It is also possible that country definitions overlap, and this is indeed the case currently with Ukraine and Russia, both of which officially report emissions in Crimea.

4.3. Other issues

Because the main energy source underlying the CDIAC-FF emissions is the UN's energy database starts in 1950 and the data sources for years before 1950 do not report sales to international bunkers, there is a jump in bunker emissions from zero in 1949 to a positive value in 1950. While at the global level this amounts to about 2% "mis-allocated" (not missing) emissions, for some countries the effect is much larger. For its size, Trinidad and Tobago was a significant producer of crude oil and products, and a large share of non-exported products were sold as international bunker fuels. Because no data for bunkers are available before 1950, this leads to an inflated estimate of territorial consumption in those years.

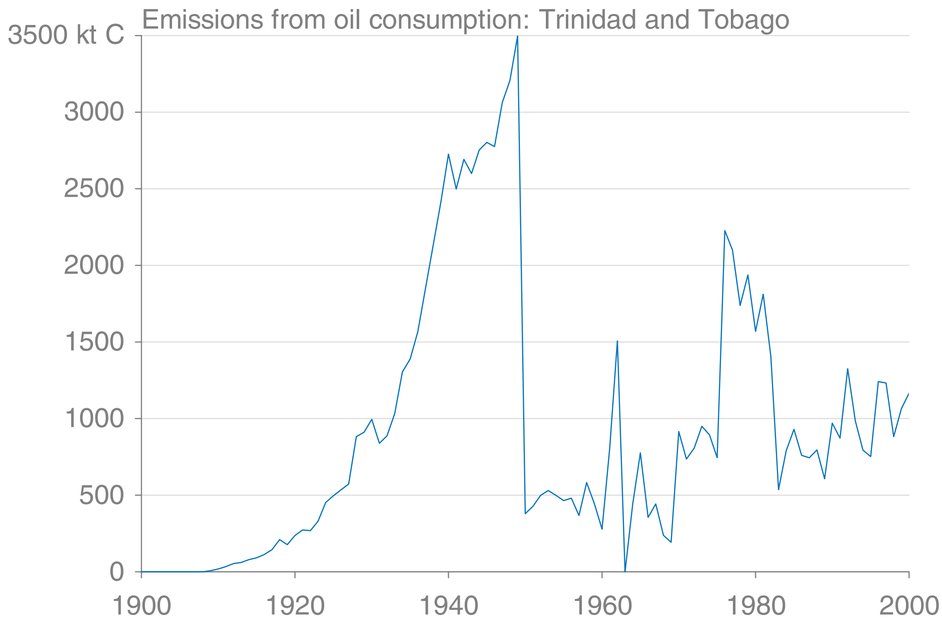

Figure 21: Emissions from oil consumption in Trinidad and Tobago, showing a large discontinuity at 1950 because of a lack of data on sales to bunkers before 1950.

In the early 19th century, energy data for some European countries (e.g., Belgium) is available only for specific years, resulting in spikes in the emissions dataset where emissions are only non-zero for a single year with zero either side. This leads to interpretation issues when rates of change are calculated.

5. FAQ

Some questions are received more frequently than others, so we will collect responses to some of these here, developing this over time.

5.1. Kuwaiti oil fires

In the dataset there is one region that does not represent a territory, and that is “Kuwaiti oil fires”. This represents the emissions from the >650 oil wells that were set alight by Iraqi troops as they retreated from Kuwait in 1991. The emissions from combustion of both oil and natural gas were estimated by CDIAC-FF to be 477 Mt CO_2 (Andres et al., 1994). This region has non-zero emissions only in the year 1991.

5.2. Aruba

Aruba is a country within the Kingdom of the Netherlands located in the Caribbean. The territory has an unusual emissions history because of the presence of a single oil refinery that, when running, substantially increases the island’s emissions (Figure 22). In 2012, this refinery was mothballed, leading to a sharp decline in the island’s emissions (McCarthy, 2016).

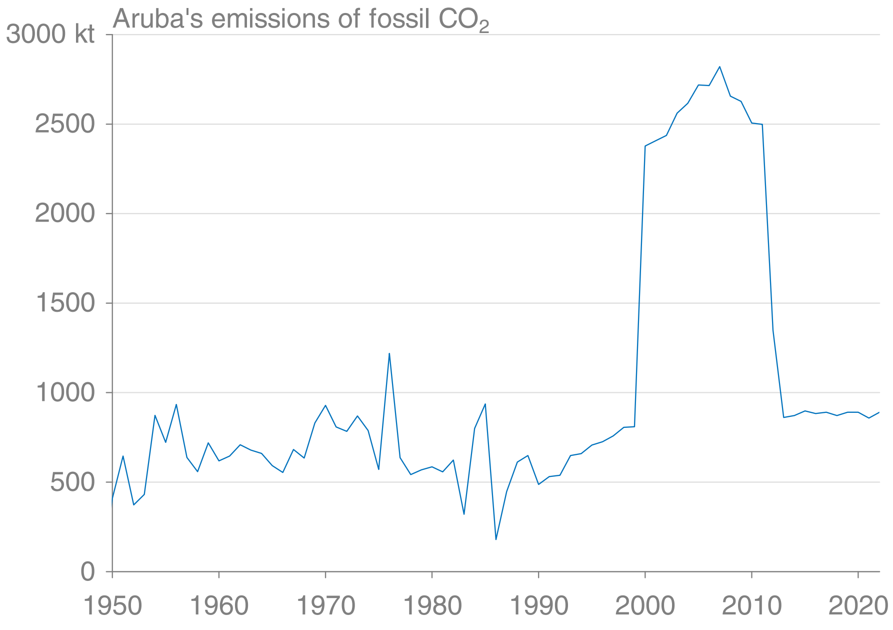

Figure 22: Emissions in Aruba, a Caribbean island, exhibiting an unusual trend.

5.3. Singapore

Singapore is a small country that sells a very large amount of fuel for international shipping and aviation. By convention, emissions from combustion of these bunker fuels, the vast majority of which does not occur in national territory, are excluded from national emissions accounts. However, a number of energy and emissions datasets include emissions from bunker fuels in national totals, assigned to the country that sells them. For the case of Singapore this leads to very different emissions estimates between datasets (Figure 23).

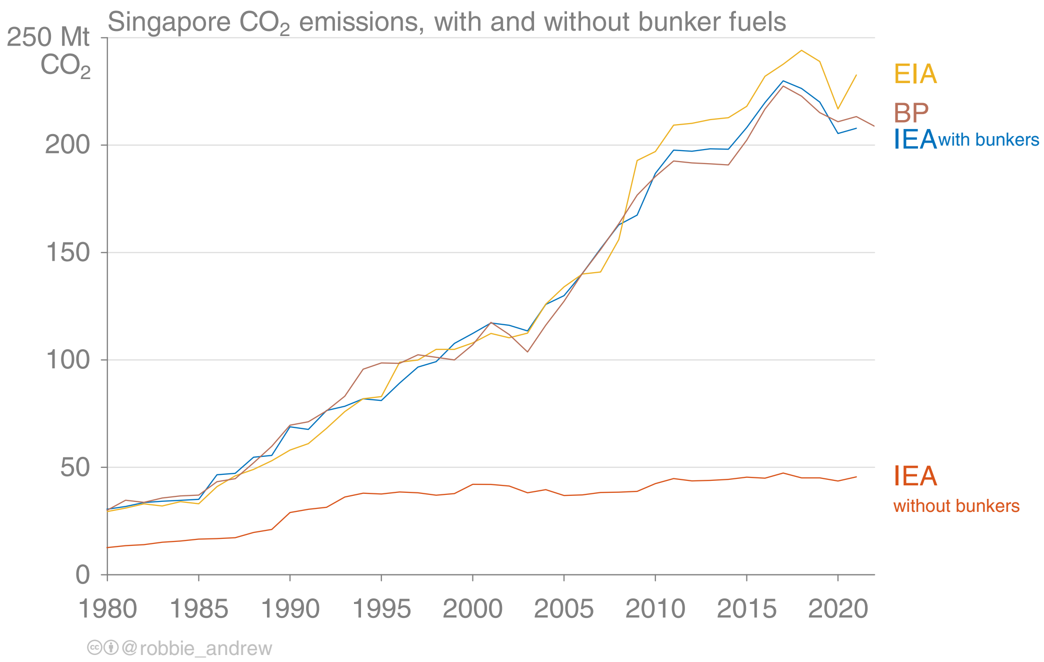

Figure 23: Singapore's CO_2 emissions as reported by several different agencies, demonstrating the very different trend when international bunkers are included.

But further than that, the estimates of Singapore's emissions from oil are highly volatile in CDIAC-FF, and therefore in GCB, because of noise in the data and the use of the reference approach.

5.4. Luxembourg

Luxembourg is a very small country that employs a significant number of people from neighbouring countries and many people commute into the country for work. One indicator of this is that about "70% of the climate emissions from fuel sales come from motor vehicles registered abroad" (Government of Luxembourg, 2020, p.62). Those who commute into Luxembourg for work are much more likely to purchase fuel in Luxembourg than in their home country because fuel taxes have long been lower in Luxembourg (IEA, 2020). This then skews statistics, because much of the fuel purchased in Luxembourg is used outside of the country, and trade statistics do not capture these movements. Given that the Reference Approach (RA) relies on trade statistics, emissions datasets that use the RA will produce incorrect estimates of Luxembourg's territorial emissions.

5.5. Nigeria

Nigeria's oil consumption is highly uncertain. Very high subsidies on fuel have led to significant undocumented smuggling across its border to neighbouring countries. Government agencies appear to have highly conflicting ideas of how much is consumed within Nigeria, and probably none of these account for black market losses (e.g., Akintayo, 2022). These subsidies were removed suddenly in 2023, which will lead to reduced domestic consumption, reduced smuggling, and possibly more accurate estimates in future.

6. Conclusions

The Global Carbon Project's fossil CO_2 emissions dataset has undergone a number of important changes over the years, and while some aspects of these changes have been reported in the annual publication of the Global Carbon Budget, detail there has necessarily been at a low level. Further, there were significant changes particularly in the 2021 edition, with more use of independent data from countries' own reporting rather than from the country>UN>CDIAC-FF route as well as somewhat reduced reliance on BP's data in the final year.

While global emissions of fossil CO_2 are relatively well characterised, particularly in relation to other greenhouse gases, the work in improving the accuracy and traceability of global fossil CO_2 estimates is ongoing, and there is considerable scope for further improvement. The relatively new use of independent approaches such as use of proxy activity data (Liu et al., 2020; Le Quéré et al., 2020) and detection of activity levels in satellite imagery (Climate TRACE, 2021) are exciting, but require a substantial investment of effort in verification and reduction in the number of assumptions required.

Capacity of governments around the world to estimate national emissions with reasonable levels of accuracy is growing and will continue to grow, but there will always be a need for independent estimates, estimates of older emissions that may not be relevant for international treaties but are vital inputs to climate science, and global collation of available data. This work will continue.

7. Acknowledgements

This work is partially funded by the Norwegian Environment Agency, together with European Commission Horizon 2020 projects VERIFY (grant no. 776810), 4C (grant no. 821003), and CoCO2 (grant no. 958927).

8. References

Akintayo, O.: Bag of controversies: Mystery of Nigeria's daily petrol consumption, Punch 5 December 2022 https://punchng.com/bag-of-controversies-mystery-of-nigerias-daily-petrol-consumption/ (Last access: 27 October 2023).

Amt für Statistik: Statistisches Jahrbuch Liechtensteins 2023, 2023. https://www.statistikportal.li/de/uebergreifendes-indikatoren/statistisches-jahrbuch (Last access: 27 October 2023).

Andres, R. J., Marland, G., Boden, T., and Bischof, S.: Carbon Dioxide Emissions from Fossil Fuel Consumption and Cement Manufacture, 1751-1991; and an Estimate of Their Isotopic Composition and Latitudinal Distribution, Snowmass Global Change Institute conference on the global carbon cycle, Snowmass, CO, 19-30 Jul 1993, 1994.access:

Andres, R. J., Fielding, D. J., Marland, G., Boden, T. A., Kumar, N., and Kearney, A. T.: Carbon dioxide emissions from fossil-fuel use, 1751–1950, Tellus B, 51 (4), 759–765, DOI: 10.3402/tellusb.v51i4.16483, 1999.

Andrew, R.: Global CO_2 emissions from cement production, 1928–2017, Earth System Science Data, 10, 2213-2239, DOI: 10.5194/essd-10-2213-2018, 2018.

Andrew, R.: A comparison of estimates of global carbon dioxide emissions from fossil carbon sources, Earth System Science Data, 12, pp 1437–1465, DOI: 10.5194/essd-12-1437-2020, 2020a.

Andrew, R.: Towards near real-time, monthly fossil CO_2 emissions estimates for the European Union with current-year projections, Atmospheric Pollution Research, DOI: 10.1016/j.apr.2021.101229, 2021.

Andrew, R.: Indian energy and emissions data, 2022. https://robbieandrew.github.io/india/ (Last access: 14 October 2022).

Andrew, R.: Global CO_2 emissions from cement production, DOI: 10.5281/zenodo.10008931, 2023a. https://zenodo.org/records/10008931 (Last access: 16 October 2023).

Andrew, R. M.: Global CO_2 emissions from cement production, 1928–2018, Earth System Science Data, 11, 1675–1710, DOI: 10.5194/essd-11-1675-2019, 2019.

Andrew, R. M.: Timely estimates of India's annual and monthly fossil CO_2 emissions, Earth System Science Data, 12 (4), 2411–2421, DOI: 10.5194/essd-12-2411-2020, 2020b.

Andrew, R. M.: Early Australian petroleum trade data, 1903-1960 [Data set], DOI: 10.5281/zenodo.7769134, 2023b. https://doi.org/10.5281/zenodo.7769134 (Last access: 25 March 2023).

BEIS: UK Greenhouse Gas Inventory, 1990 to 2019, Department for Business, Energy & Industrial Strategy, 2021. https://unfccc.int/ghg-inventories-annex-i-parties/2021 (Last access: 16 June 2021).

BEIS: UK territorial greenhouse gas emissions national statistics, Department for Business, Energy & Industrial Strategy, various years. https://www.gov.uk/government/collections/uk-territorial-greenhouse-gas-emissions-national-statistics (Last access: 16 August 2023).

Bing, L., Ma, M., Liu, L., Wang, J., Niu, L., and Xi, F.: An investigation of the global uptake of CO2 by lime from 1930 to 2020, Earth Syst. Sci. Data, 15 (6), 2431-2444, DOI: 10.5194/essd-15-2431-2023, 2023.

BP: BP Statistical Review of World Energy 2021, 2021. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html (Last access: 8 July 2021).

CBS: Maand- en kwartaalraming broeikasgasemissies conform IPCC (*Monthly and quarterly estimate of greenhouse gas emissions in accordance with IPCC*), Statistics Netherlands, The Hague, (in Dutch), 2020. https://www.cbs.nl/nl-nl/maatwerk/2020/37/maand-en-kwartaalraming-broeikasgasemissies-conform-ipcc (Last access: 19 January 2021).

Cerdeiro, D. A., Komaromi, A., Liu, Y., and Saeed, M.: World Seaborne Trade in Real Time: A Proof of Concept for Building AIS-based Nowcasts from Scratch, International Monetary Fund (IMF), WP/20/57, 2020. https://www.imf.org/en/Publications/WP/Issues/2020/05/14/World-Seaborne-Trade-in-Real-Time-A-Proof-of-Concept-for-Building-AIS-based-Nowcasts-from-49393 (Last access: October 2023).

CITEPA: Secten – le rapport de référence sur les émissions de gaz à effet de serre et de polluants atmosphériques en France, various years. https://www.citepa.org/fr/secten/ (Last access: 9 May 2022).

Clarke, D., Flachenecker, F., Guidetti, E., and Pionnier, P.-A.: CO_2 Emissions from air transport: A near-real-time global database for policy analysis, Organization for Economic Co-operation and Development, Paris, OECD Statistics Working Papers 2022/04, 2022. https://dx.doi.org/10.1787/ecc9f16b-en (Last access: February 2023).

Climate TRACE, 2021. https://www.climatetrace.org/ (Last access: 16 September 2021).

Cui, D., Deng, Z., and Liu, Z.: China's non-fossil fuel CO2 emissions from industrial processes, Applied Energy, 254, 113537, DOI: https://doi.org/10.1016/j.apenergy.2019.113537, 2019.

DCCEEW: Australian Energy Update, Department of Climate Change, Energy, the Environment and Water, various years. https://www.energy.gov.au/publications?title=energy%20update&sort_by=field_date_value (Last access: 16 August 2023).

DCE: Denmark's National Inventory Report 2021, Danish Centre for Environment and Energy, Aarhus, 2021. https://unfccc.int/ghg-inventories-annex-i-parties/2021 (Last access: 16 June 2021).

DCE: Denmark's National Inventory Report 2023, Danish Centre for Environment and Energy, Aarhus, 2023. https://unfccc.int/ghg-inventories-annex-i-parties/2023 (Last access: 16 August 2023).

DIMENC: l'Observatoire de l'Energie en Nouvelle-Calédonie, Direction de l'Industrie, des Mines et de l'Energie, *various years*. https://observatoire-energie.gouv.nc/public/home/ (Last access: 31 October 2023).

DISER: National Inventory Report 2019: The Australian Government Submission to the United Nations Framework Convention on Climate Change, Department of Industry, Science, Energy and Resources, 2021. www.unfccc.int (Last access: 13 September 2021).

DISER: National Greenhouse Gas Inventory: Quarterly updates, Australian Government: Department of Industry, Science, Energy and Resources, various years. https://www.industry.gov.au/data-and-publications/national-greenhouse-gas-inventory-quarterly-updates (Last access: 21 January 2021).

EEA: EIONET: Central Data Repository, European Environment Agency, 2023. https://cdr.eionet.europa.eu/ (Last access: 2 March 2023).

EIA: International Energy Statistics, Energy Information Administration, *no date*. https://www.eia.gov/beta/international/data/browser/ (Last access: 31 August 2019).

EIA: Short-Term Energy Outlook, U.S. Energy Information Administration, various years. https://www.eia.gov/outlooks/steo/ (Last access: October 2023).

Elvidge, C. D., Ziskin, D., Baugh, K. E., Tuttle, B. T., Ghosh, T., Pack, D. W., Erwin, E. H., and Zhizhin, M.: A Fifteen Year Record of Global Natural Gas Flaring Derived from Satellite Data, Energies, 2 (3), 595-622, 2009.

EnerData: Global Energy Trends: 2021 edition, 2021. https://www.enerdata.net/ (Last access: 26 July 2021).

Energy Institute: Statistical Review of World Energy, 2023. https://www.energyinst.org/statistical-review (Last access: 26 June 2023).

Energy Institute: Statistical Review of World Energy, various years. https://www.energyinst.org/statistical-review (Last access: 26 June 2023).

EPA: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2019, U.S. Environmental Protection Agency, Washington, DC, 2021. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks (Last access: 11 June 2021).

EPA: Republic of China National Greenhouse Gas Inventory Report 2022, Taiwan Environmental Protection Administration, 2022. https://unfccc.saveoursky.org.tw/nir/tw_nir_2022.php (Last access: 23 March 2023).

Etemad, B., and Luciani, J.: World Energy Production 1800-1985, Librairie Droz, ISBN 2600560076, 1991.

European Commission: Commission Implementing Regulation (EU) 2020/1208, 2020. https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A32020R1208 (Last access: 28 March 2023).

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Quéré, C. L., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S., Aragão, L. E. O. C., Arneth, A., Arora, V., Bates, N. R., Becker, M., Benoit-Cattin, A., Bittig, H. C., Bopp, L., Bultan, S., Chandra, N., Chevallier, F., Chini, L. P., Evans, W., Florentie, L., Forster, P. M., Gasser, T., Gehlen, M., Gilfillan, D., Gkritzalis, T., Gregor, L., Gruber, N., Harris, I., Hartung, K., Haverd, a., Houghton, R. A., Ilyina, T., Jain, A. K., Joetzjer, E., Kadono, K., Kato, E., Kitidis, V., Korsbakken, J. I., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Liu, Z., Lombardozzi, D., Marland, G., Metzl, N., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S.-I., Niwa, Y., O'Brien, K., Ono, T., Palmer, P. I., Pierrot, D., Poulter, B., Resplandy, L., Robertson, E., Rödenbeck, C., Schwinger, J., Séférian, R., Skjelvan, I., Smith, A. J. P., Sutton, A. J., Tanhua, T., Tans, P. P., Tian, H., Tilbrook, B., Werf, G. v. d., Vuichard, N., Walker, A. P., Wanninkhof, R., Watson, A. J., Willis, D., Wiltshire, A. J., Yuan, W., Yue, X., and Zaehle, S.: Global Carbon Budget 2020, Earth System Science Data, 12, 3269–3340, DOI: 10.5194/essd-12-3269-2020, 2020.

GCP: About GCP, Global Carbon Project, no date. https://www.globalcarbonproject.org/about/index.htm (Last access: 23 September 2021).

GGFR: Global Gas Flaring Data, Global Gas Flaring Reduction Partnership, World Bank, Payne Institute, and Colorado School of Mines, various years. https://www.worldbank.org/en/programs/gasflaringreduction/global-flaring-data (Last access: 13 September 2022).

Gilfillan, D., and Marland, G.: CDIAC-FF: global and national CO2 emissions from fossil fuel combustion and cement manufacture: 1751–2017, Earth Syst. Sci. Data, 13 (4), 1667-1680, DOI: 10.5194/essd-13-1667-2021, 2021.

Global Energy Monitor: Global Coal Plant Tracker, 2023. https://globalenergymonitor.org/projects/global-coal-plant-tracker/ (Last access: 28 March 2023).

Government of Luxembourg: Luxembourg's Integrated National Energy And Climate Plan For 2021-2030, 2020. https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en (Last access: October 2023).

Haukås, H. T., Jaques, A., Neitzert, F., Rosland, A., Rypdal, K., and Weidemann, F.: Chapter 2: Industrial Processes, in: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual, edited by: Houghton, J. T., Meira Filho, L. G., Lim, B., Tréanton, K., Mamaty, I., Bonduki, Y., Griggs, D. J., and Callander, B. A., IPCC/OECD/IEA, Paris, 1997. http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.html (Last access: 27 October 2014).

Hefner, M., and Marland, G.: Global, Regional, and National Fossil-Fuel CO2 Emissions: 1751-2020 CDIAC-FF, Research Institute for Environment, Energy, and Economics, Appalachian State University, 2023. https://energy.appstate.edu/research/work-areas/cdiac-appstate (Last access:

IEA: World Energy Balances 2019 Edition: Database Documentation, International Energy Agency, Paris, 2019. www.iea.org (Last access: 29 August 2019).

IEA: Luxembourg 2020: Energy Policy Review, International Energy Agency, Paris, 2020. https://www.iea.org/reports/luxembourg-2020 (Last access: October 2023).

IFA: Consumption, International Fertilizer Association, various years. https://www.ifastat.org/databases/plant-nutrition (Last access: 18 August 2023).

JODI: JODI website, Joint Organisations Data Initiative, *no date*. https://www.jodidata.org/ (Last access: 24 January 2024).

Ke, J., McNeil, M., Price, L., Khanna, N. Z., and Zhou, N.: Estimation of CO2 emissions from China's cement production: Methodologies and uncertainties, Energy Policy, 57 (0), 172-181, DOI: http://dx.doi.org/10.1016/j.enpol.2013.01.028, 2013.

KEEI: Korea Energy Statistical Information System, Korea Energy Economics Institute, Seoul, 2022. http://www.kesis.net/main/mainEng.jsp (Last access: 15 October 2022).

Keeling, C. D.: Industrial production of carbon dioxide from fossil fuels and limestone, Tellus, 25 (2), 174-198, DOI: 10.3402/tellusa.v25i2.9652, 1973.

Keidel, A.: China's Economic Fluctuations and Their Implications for Its Rural Economy, Carnegie Endowment for International Peace, Washington, D.C., 2007.access:

Klif: National Inventory Report 2010 - Norway, Klima- og forurensningsdirektoratet, Oslo, TA 2639/2010, 2010. www.unfccc.int (Last access: 9 September 2021).

Korsbakken, J. I., Peters, G. P., and Andrew, R. M.: Uncertainties around reductions in China's coal use and CO_2 emissions, Nature Climate Change, 6, 687–690, DOI: 10.1038/nclimate2963, 2016.

Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., Pickers, P., Korsbakken, J. I., Peters, G. P., Canadell, J. G., Arneth, A., Arora, V. K., Barbero, L., Bastos, A., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Doney, S. C., Gkritzalis, T., Goll, D. S., Harris, I., Haverd, V., Hoffman, F. M., Hoppema, M., Houghton, R. A., Ilyina, T., Jain, A. K., Johannesen, T., Jones, C. D., Kato, E., Keeling, R. F., Goldewijk, K. K., Landschützer, P., Lefèvre, N., Lienert, S., Lombardozzi, D., Metzl, N., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S. I., Neill, C., Olsen, A., Ono, T., Patra, P., Peregon, A., Peters, W., Peylin, P., Pfeil, B., Pierrot, D., Poulter, B., Rehder, G., Resplandy, L., Robertson, E., Rocher, M., Rödenbeck, C., Schuster, U., Schwinger, J., Séférian, R., Skjelvan, I., Steinhoff, T., Sutton, A., Tans, P. P., Tian, H., Tilbrook, B., Tubiello, F. N., van der Laan-Luijkx, I. T., van der Werf, G. R., Viovy, N., Walker, A. P., Wiltshire, A. J., Wright, R., and Zaehle, S.: Global Carbon Budget 2018, Earth System Science Data, 10, 2141-2194, DOI: 10.5194/essd-10-2141-2018, 2018.

Le Quéré, C., Jackson, R. B., Jones, M. W., Smith, A. J. P., Abernethy, S., Andrew, R. M., De-Gol, A. J., Willis, D. R., Shan, Y., Canadell, J. G., Friedlingstein, P., Creutzig, F., and Peters, G. P.: Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement, Nature Climate Change, DOI: 10.1038/s41558-020-0797-x, 2020.

Liu, F., and Wang, S.: The Building Materials Industry in China: An Overview, Lawrence Berkeley Laboratory, University of California, DOI: 10.2172/94549, 1994. https://doi.org/10.2172/94549 (Last access: 11 May 2021).

Liu, Z., Ciais, P., Deng, Z., Davis, S. J., Zheng, B., Wang, Y., Cui, D., Zhu, B., Dou, X., and Ke, P.: Carbon Monitor, a near-real-time daily dataset of global CO 2 emission from fossil fuel and cement production, Scientific data, 7 (1), 1-12, 2020.

Maddison, A.: Historical Statistics of the World Economy: 1-2008 AD, 2010. http://www.ggdc.net/maddison/oriindex.htm (Last access: 9 March 2021).

McCarthy, J.: Citgo To Pour Up To $600 Million Into Refurbishing Mothballed Aruba Oil Refinery, Virgin Islands Free Press 23 June 2016 https://web.archive.org/web/20211013155312/https://vifreepress.com/2016/06/citgo-pour-600-million-refurbishing-mothballed-aruba-oil-refinery/ (Last access: October 2023).

MEER: Handbook Of Energy & Economic Statistics of Indonesia, Ministry of Energy and Mineral Resources, Republic of Indonesia, various years. https://www.esdm.go.id/en/publication/handbook-of-energy-economic-statistics-of-indonesia-heesi (Last access: 10 May 2022).

MFA, and MSTI: Fourth Biennial Update Report of Brazil to the United Nations Framework Convention on Climate Change, Ministry of Foreign Affairs and Ministry of Science, Technology and Innovations, 2020. www.unfccc.int (Last access: 25 June 2021).

Miljødirektoratet: Greenhouse Gas Emissions 1990–2019, National Inventory Report, The Norwegian Environment Agency, Oslo, M-2013/2021, 2021. https://www.miljodirektoratet.no/ (Last access: 9 September 2021).

Ministry of Environment: 2021 National Greenhouse Gas Inventory Report of Korea, Greenhouse Gas Inventory and Research Center, 2021. http://www.gir.go.kr/eng/ (Last access: 11 January 2022).

Mitchell, B. R.: International Historical Statistics : The Americas : 1750-1988, Stockton Press, New York, ISBN 978-1-349-13073-3, 1993.

MNRE: Thailand's Fourth Biennial Update Report, Ministry of Natural Resources and Environment, 2022.access:

MoE: Energy Statistics, Energy Policy and Planning Office of the Thai Ministry of Energy, various years. https://www.eppo.go.th/index.php/en/en-energystatistics/summary-statistic (Last access: 19 August 2023).

Mohr, S. H., Wang, J., Ellem, G., Ward, J., and Giurco, D.: Projection of world fossil fuels by country, Fuel, 141, 120-135, DOI: http://dx.doi.org/10.1016/j.fuel.2014.10.030, 2015.

MTE: Stratégie Nationale Bas-Carbone (SNBC), Ministère de la Transition écologique, 2021. https://www.ecologie.gouv.fr/strategie-nationale-bas-carbone-snbc (Last access: 24 September 2021).

Myhre, G., Alterskjær, K., and Lowe, D.: A fast method for updating global fossil fuel carbon dioxide emissions, Environmental Research Letters, 4 (3), 034012, DOI: 10.1088/1748-9326/4/3/034012, 2009.

Pollard, S.: A New Estimate of British Coal Production, 1750–1850, The Economic History Review, 33 (2), 212-235, DOI: 10.2307/2595840, 1980.

Raupach, M. R., Marland, G., Ciais, P., Le Quéré, C., Canadell, J. G., Klepper, G., and Field, C. B.: Global and regional drivers of accelerating CO2 emissions, Proceedings of the National Academy of Sciences, 104 (24), 10288–10293, DOI: 10.1073/pnas.0700609104, 2007.

Rotty, R. M.: Commentary on and extension of calculative procedure for CO_2 production, Tellus, 25 (5), 508-517, DOI: doi:10.1111/j.2153-3490.1973.tb00635.x, 1973.

Rypdal, K.: CO_2 emission estimates for Norway: Methodological difficulties, Statistisk sentralbyrå, Oslo, Documents 2001/14, 2001. https://www.ssb.no/en/natur-og-miljo/artikler-og-publikasjoner/co2-emission-estimates-for-norway (Last access: 23 September 2021).

SFT: National Inventory Report 2002: Norway, Statens forurensningstilsyn, Oslo, TA-1886/2002, ISBN 82-7655-455-5, 2002. https://www.miljodirektoratet.no/ (Last access: 9 September 2021).

Shan, Y., Liu, Z., and Guan, D.: CO_2 emissions from China's lime industry, Applied Energy, 166, 245-252, DOI: https://doi.org/10.1016/j.apenergy.2015.04.091, 2016.

SSB: Table 09261: Greenhouse gases, acidifying gases etc., by source and pollutant (closed series) 1973 - 2008, Statistics Norway, 2012. https://www.ssb.no/en/statbank/table/09261/ (Last access: 3 September 2019).

SSB: Table 10800: Greenhouse gases, by source, energy product and pollutant (closed series) 1980 - 2012, Statistics Norway, 2015. https://www.ssb.no/en/statbank/table/10800/ (Last access: 3 September 2019).

SSB: Table 08940: Greenhouse gases, by source, energy product and pollutant 1990 - 2020, Statistics Norway, Oslo, 2021. https://www.ssb.no/en/statbank/table/08940/ (Last access: 30 June 2021).

Statistics Finland: 138v - Greenhouse gas emissions in Finland, 2023. https://pxweb2.stat.fi/PxWeb/pxweb/en/StatFin/StatFin__khki/statfin_khki_pxt_138v.px/ (Last access: 15 June 2023).

Statistics Iceland: Gross energy consumption by source 1940-2020, *Various years-a*. https://px.hagstofa.is/pxen/pxweb/en/Umhverfi/Umhverfi__4_orkumal__2_framleidslaognotkun/IDN02102.px/ (Last access: 27 October 2023).

Statistics Iceland: Losun gróðurhúsalofttegunda frá hagkerfi Íslands, bráðabirgðartölur, *various years-b*. https://px.hagstofa.is/pxen/pxweb/en/Umhverfi/Umhverfi__2_losunlofttegunda__2_losunlofttegunda_aea/UMH31109.px (Last access: 4 November 2023).

Statistics Sweden: Total emissions and removals of greenhouse gases by greenhouse gas and sector. Year 1990 - 2021, 2023. https://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__MI__MI0107/TotaltUtslappN/ (Last access: 28 March 2023).

UBA: UBA-Prognose: Treibhausgasemissionen sanken 2022 um 1,9 Prozent, Umwelt Bundesamt, 2023. https://www.umweltbundesamt.de/presse/pressemitteilungen/uba-prognose-treibhausgasemissionen-sanken-2022-um (Last access: 15 March 2023).

UN: World Population Prospects, United Nations, Department of Economic and Social Affairs, Population Division, various years. https://population.un.org/wpp/ (Last access: 8 September 2021).

UNFCCC: Review Process, United Nations Framework Convention on Climate Change, no date. https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/review-process (Last access: 9 September 2021).

USGS: Lime statistics, in: Historical statistics for mineral and material commodities in the United States: U.S. Geological Survey Data Series 140, edited by: Kelly, T. D., and Matos, G. R., U.S. Geological Survey, 2017. https://minerals.usgs.gov/minerals/pubs/historical-statistics (Last access: 26 March 2021).

Wikipedia: 1991 Zaire unrest, 2023. https://en.wikipedia.org/w/index.php?title=1991_Zaire_unrest&oldid=1142445029 (Last access: 28 March 2023).

Yáñez, C., Rubio Varas, M. d. M., Jofré González, J., and Carreras Marín, A.: El consumo aparente de carbón mineral en América Latina, 1841-2000. Una historia de progreso y frustración, Revista de Historia Industrial, 53 (3), 25-77, 2013.

Appendix: Change Log

2021v34, published 14 October 2021

- Modified method of extrapolation using BP energy data for oil emissions to recognise that BP's national oil data include sales to international bunker. This correction allowed the maintenance of the global total change in oil emissions in 2020 to match the global total change in oil consumption in energy terms reported by BP (see section 2.2.27).
- Added data from CBS for the Netherlands (see section 2.2.6).

2022v27, published 17 October 2022

- For non-Annex 1 countries, we have used satellite-derived estimates of flaring reported by the World Bank's Global Gas Flaring Reporting (GGFR) Partnership starting from 2012. The use of these data for Annex 1 countries is still being considered.
- New estimates of Chinese coal consumption 1907–1949 based on information from historian Tim Wright.
- Added preliminary estimates from Statistics Finland for the year following the final year of their most recent submission to the UNFCCC.
- Adjustments to international bunker emissions based on additional data from Marine Benchmark and the EIA.
- CDIAC's 2022 pre-release had negative emissions for UAE and Oman in 2019, a result of incorrect energy reporting by these two countries, so we have replaced from 2017 using growth rates from BP's energy data.
- CDIAC's 2022 pre-release had a doubling of Colombia's emissions from natural gas, which is inconsistent with other sources, so we have replaced with CDIAC's 2021 release, which does not exhibit the same errors.

2023v28, published 2 November 2023

- Added additional country disaggregations for French Equatorial Africa and French West Africa before 1960
- Used EIA data for DR Congo coal after 1990
- New series for early UK coal
- New series for Australian coal before 1990, coal 1960-1989, oil before 1960
- Replaced use of BP/EI data with extensions using UN energy data and JODI natural gas data for final years, where available
- Specific estimate for Ukraine in 2022
- Use of official low-lag estimates for Thailand
- Estimation from Iceland's energy data 1940-1949
- Estimation from Liechtenstein's energy data 1959-1989
- Addition of earlier satellite-derived flaring estimates
- New methods for international bunkers in final years

2023v36, published 21 November 2023

- New data for New Caledonia
- New data for Iceland's final year
- Split of international bunkers by aviation and shipping
- Norway updated from official 2023 release

2023v43, published 24 January 2024

- New coal emissions for 20 Latin American countries estimated from data collated by Yáñez et al. (2013)
- Further work identifying true zeros and true NaNs (=NODATA)
- Clear indication of source as CDIAC (Andres et al. 2011) before 1950 where appropriate
- Various updates to countries for which low-lag data are available
- Corrected errors:
  - Some data were incorrect processed in per capita series
  - Some sources were incorrect for disaggregated countries