The Global Carbon Project's fossil CO_2 emissions dataset: 2021 release

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

[internal version GCB2021v34]

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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 2021 release of the GCP's fossil CO_2 emissions dataset.

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

[1] Apparent consumption is derived from production, export, import, and stock change data. It contrasts to observed consumption, collated from alternative sources such as direct consumption reporting by industry. The Reference Approach to calculating emissions uses apparent consumption of energy products, while the Sectoral Approach uses alternative approaches.

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

2. Methods

The GCP's fossil CO_2 emissions dataset begins with CDIAC-FF (Gilfillan and Marland, 2021), extended by 2-3 years using energy growth rates derived from BP's data (Myhre et al., 2009; BP, 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. 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 reporting practice. For GCB version 2021v34 we use CDIAC-FF 2021 (pers. comm., Gregg Marland, 29 September 2021).

BP releases its Statistical Review of World Energy in June or July every year, being the first freely available global update of energy up to the previous year (e.g., BP, 2021). Since the UN data used by CDIAC-FF lag by two years, BP's data have proved useful in extending the emissions series (Myhre et al., 2009; Friedlingstein et al., 2020). While BP'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 BP data to extend emissions estimates, therefore, it is necessary to apply the growth rate from each of these groups to all countries falling within the group, introducing some additional uncertainty.

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 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'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. However, CDIAC'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, BP, 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'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 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 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's data contain implausible values (e.g., negatives) or rates of change (e.g., sudden, unexplainable spikes or steps), or where checking against sources used by CDIAC 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. 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. These reports are disaggregated according to the IPCC 'sector' framework, which we then map to the components used by CDIAC: 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's categories, namely decomposition of carbonates in IPCC sector 2 (industrial processes and product use) apart from in cement production (2A).

Most emissions can be mapped directly to CDIAC'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 solid, liquid, and gaseous fuels.

The first deadline 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 2021 release of GCB we have used the Excel files from the UNFCCC downloaded on 11 June 2021.

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 almost 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 2.2.14 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, 2021a), the UK does not submit data to the UNFCCC based on this geographical definition, and the GBK geography is closest.

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 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 feedstock 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 effort is focussed more on energy used within the territory than energy sent out of it.

Since CDIAC uses apparent consumption, equivalent to what the IPCC call the reference approach, CDIAC'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, 2021a, 2015, 2012). These series begin in 1973, which is when oil production began in Norway: at that time CDIAC's estimates match Norway's own, and the problem with the apparent consumption approach only becomes significant as oil (and gas) production grow in subsequent years; CDIAC'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's components for continuity of the series.

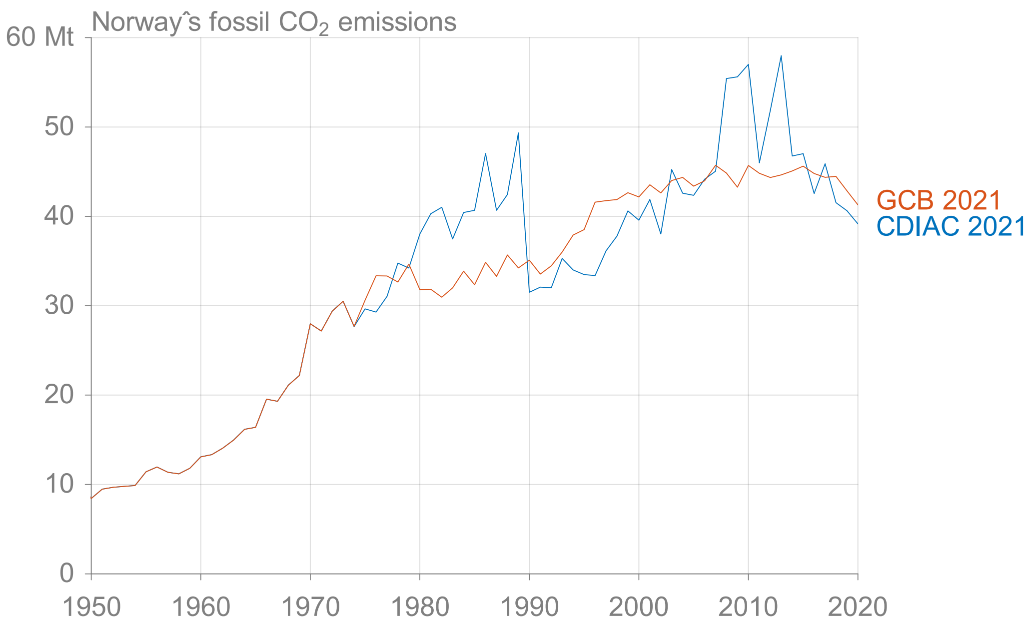

Figure 1: Comparison of estimated fossil CO_2 emissions for Norway from CDIAC-FF (Gilfillan et al., 2020) and GCP (this work).

2.2.3. China's emissions from lime production

While we use CDIAC'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 1.

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.

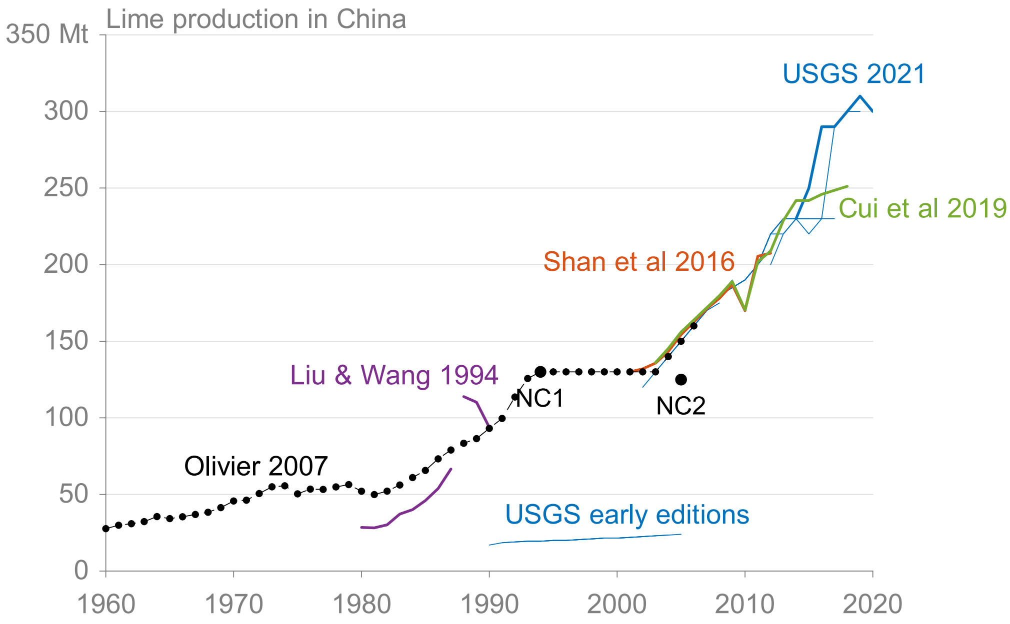

Figure 2: China's production of lime as reported by a range of sources. There is a gap in the data from Liu & Wang (purple line).

From these activity data we apply the emission factor used by Shan et al. (2016) (0.683 kg CO_2 / kg lime) for fossil CO_2 emissions from the decomposition of carbonates in the production of lime and arrive at the estimates shown in Figure 2. Uncertainty remains very high for estimates before 1988, and no estimates are available before 1960.

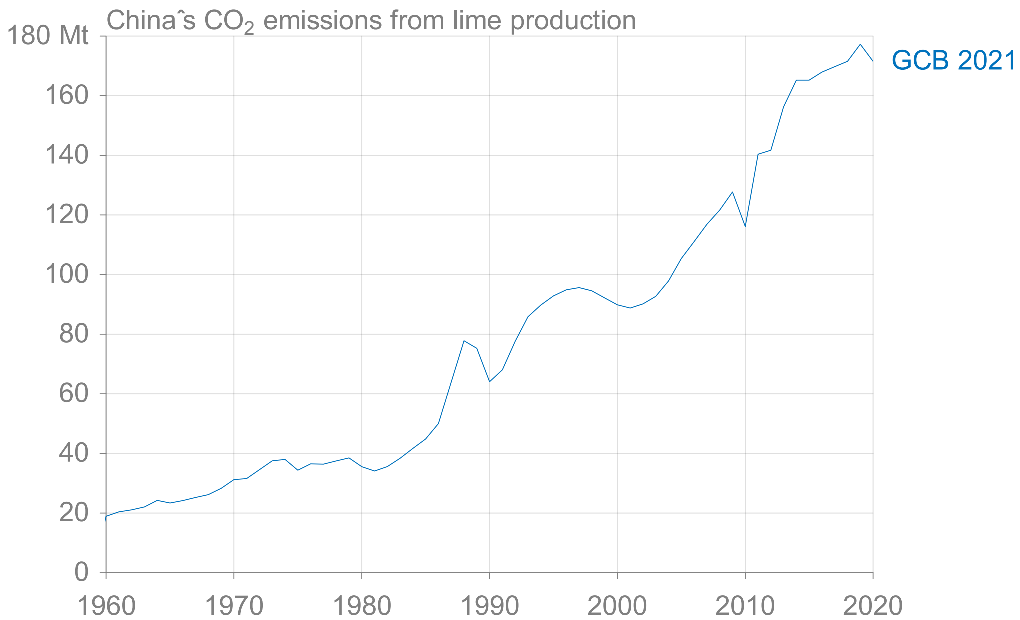

Figure 3: Estimated CO_2 emissions from China's lime production. No data are available before 1960.

2.2.4. Indonesia

CDIAC'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's coal emissions for Indonesia with our own estimates based on coal consumption data officially reported by the country (MEER, 2021).

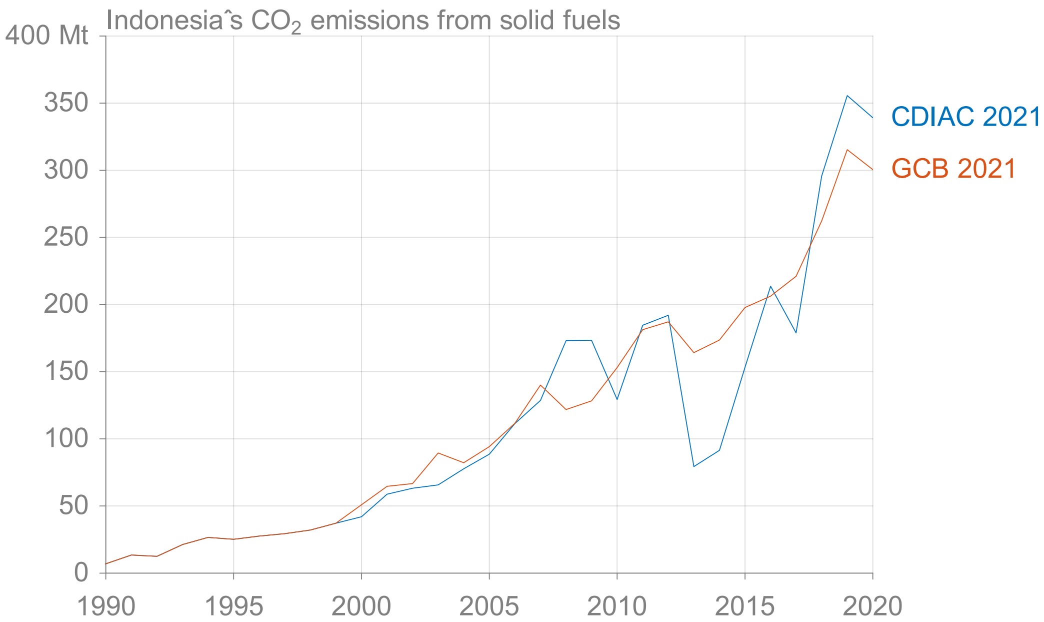

Figure 4: Comparison of Indonesia's CO_2 emissions from solid fuels in CDIAC-FF and GCB (this work).

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, 2021b). 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.

2.2.6. Netherlands

The Netherlands recently began publishing quarterly estimates of territorial emissions (Andrew, *Accepted;* CBS, 2020). We have used published total CO_2 emissions for the two years available, 2019 and 2020.

2.2.7. 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 in this period (EIA, 2021). 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'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.

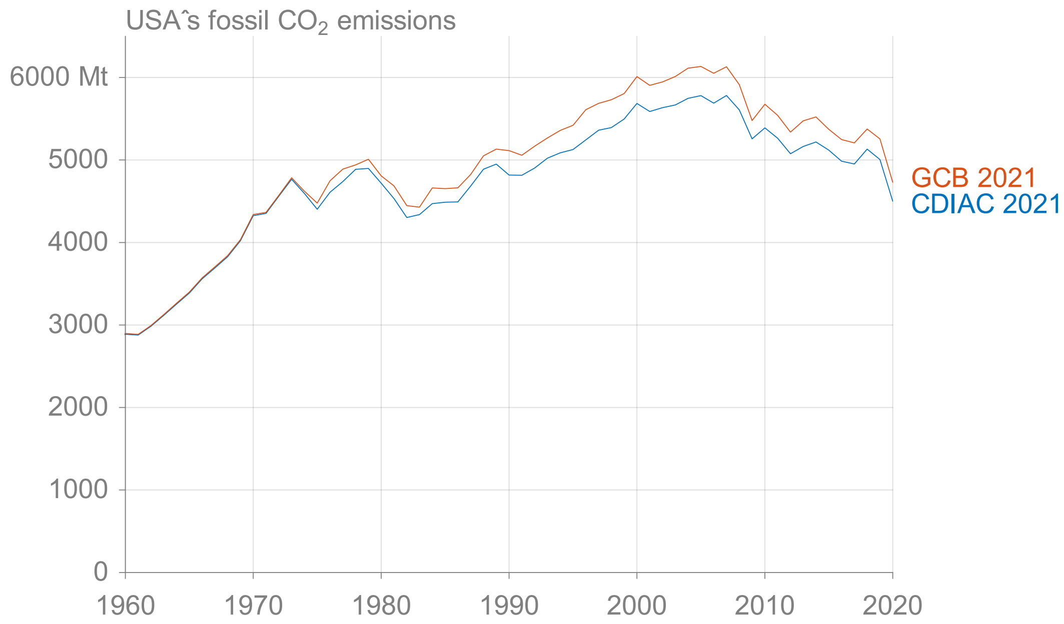

Figure 5: US fossil CO_2 emissions from CDIAC-FF 2020 and GCB 2021 (this work).

2.2.8. India

Andrew (2020b) introduced a new method for estimating fossil CO_2 emissions in India using monthly activity data (Andrew, 2021a), and annual estimates derived from these were first incorporated into the GCP’s fossil CO_2 dataset in 2020. Importantly, other datasets, including both 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 5). 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 2-3 months.

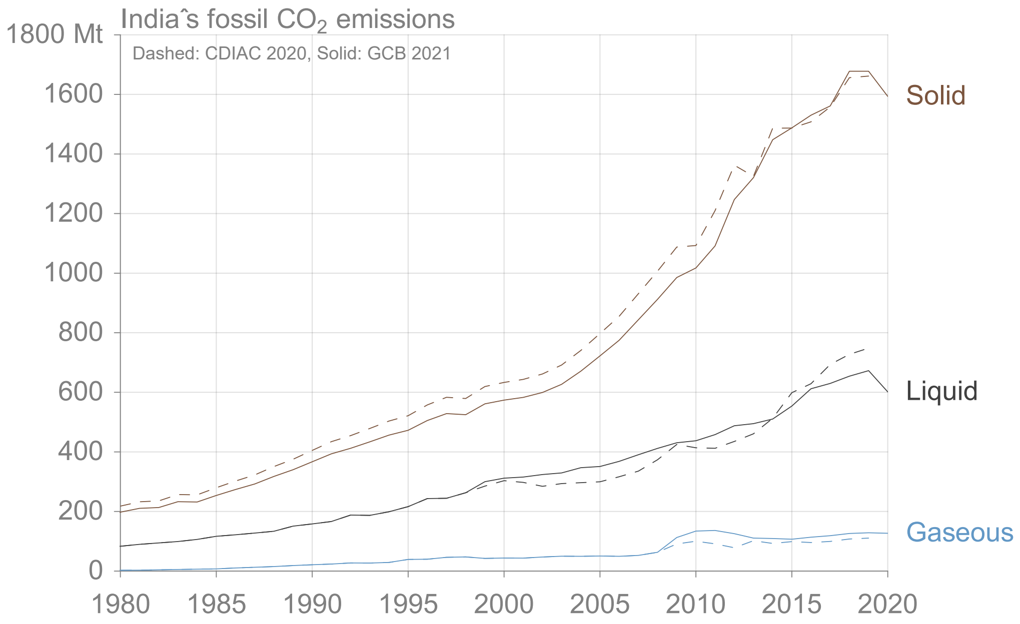

Figure 6: India's fossil CO_2 emissions from CDIAC-FF 2020 and GCB 2021, the latter updated from Andrew (2020b).

2.2.9. 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, 2020). Total fossil CO_2 emissions and CO_2 emissions from cement production over 1990–2018 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 (2021) 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 1981–2020.

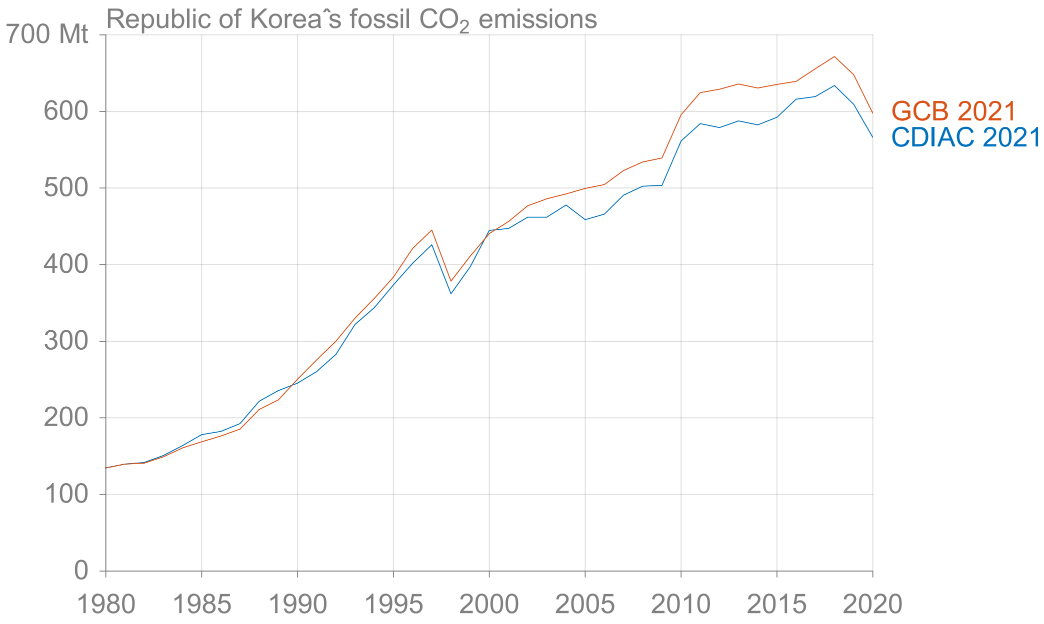

Figure 7: South Korea's fossil CO_2 emissions from CDIAC-FF 2020 and GCB 2021 (this work), the latter taken directly from official reporting for 1990–2018 and derived from detailed energy data 1981–2020.

2.2.10. Greenland

Denmark reports Greenland's emissions as part of Denmark's national greenhouse gas inventory in tables in Chapter 16 of the report (DCE, 2021). These have been assembled and we use the total fossil CO_2 emissions for 1990–2019 (Figure 6) and scale components to match the new totals.

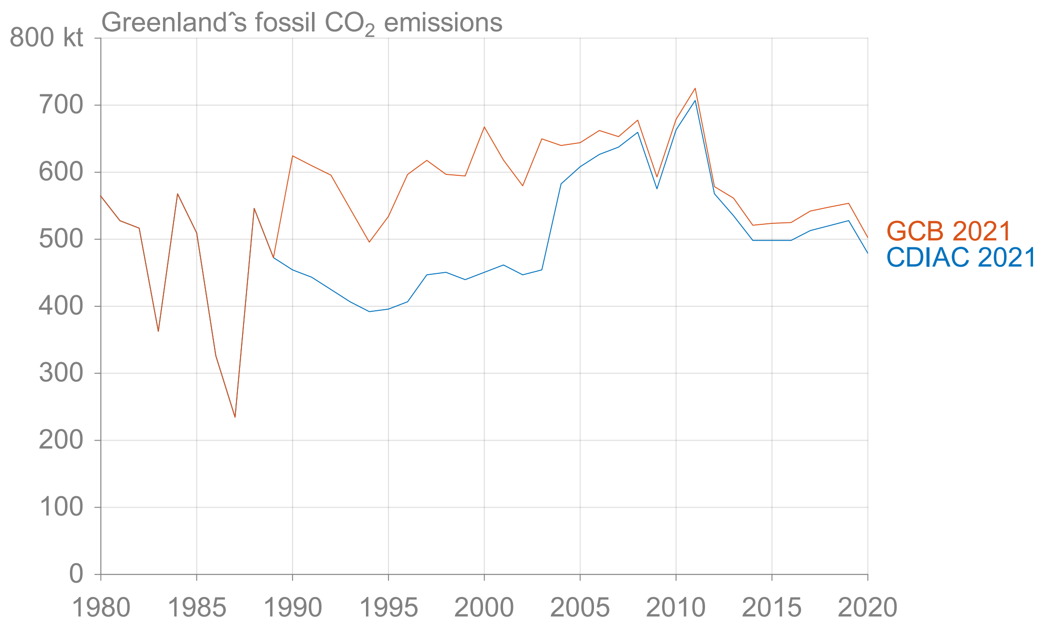

Figure 8: Greenland's fossil CO_2 emissions from CDIAC-FF 2020 and GCB 2021 (this work), the latter taken directly from official reporting.

2.2.11. 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.

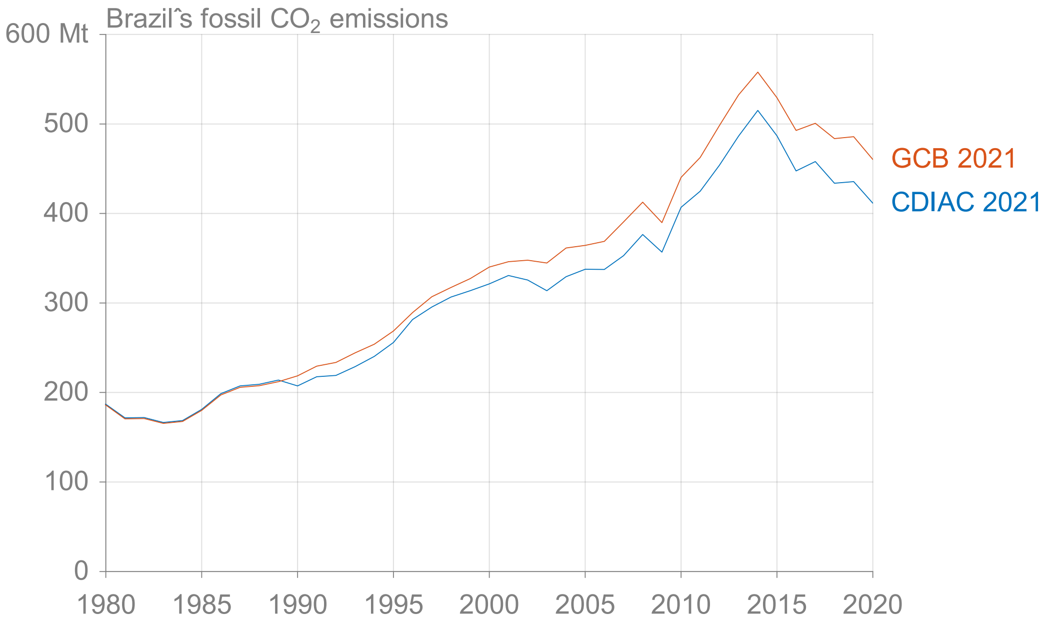

Figure 9: Comparison of Brazil's fossil CO_2 emissions in CDIAC-FF and GCP (this work), the latter taken directly from official reporting.

2.2.12. 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, 2020). While CDIAC's estimates from UN energy data look robust between 1990 and 2000, some divergence is evident after 2000 (Figure 7).

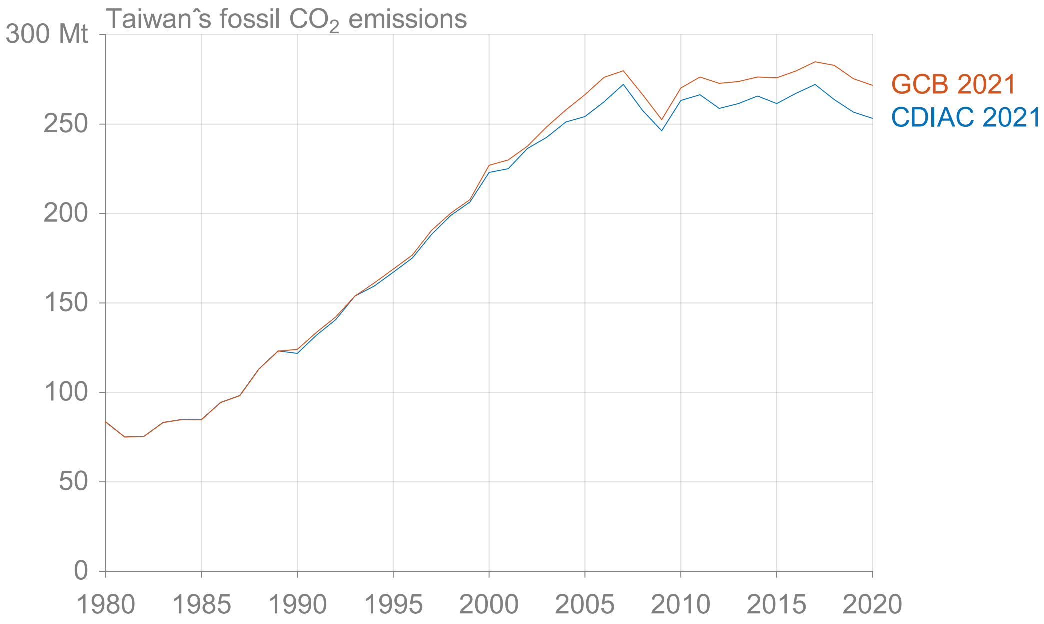

Figure 10: Taiwan's fossil CO_2 emissions from CDIAC-FF and GCB 2021 (this work), the latter directly from official reporting.

2.2.13. Germany

For Germany's emissions in 2020, we use the total reported by the Federal Environment Ministry (UBA, 2021), and scale the components the small amount necessary to match the total.

2.2.14. 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). In 2021, we have further revised this. Australia reports to the UNFCCC for its fiscal year, July-June, rather than the internationally normal calendar year (DISER, 2021b). For the period 1990–2020 we therefore use calendar-year fossil CO_2 emissions estimates derived from Australia's quarterly updates of its NGHGI (DISER, 2021a).

2.2.15. 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, 2021).

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-Barthélémy, 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 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'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's data, resulting in approximate estimates beyond 2010 for these territories.

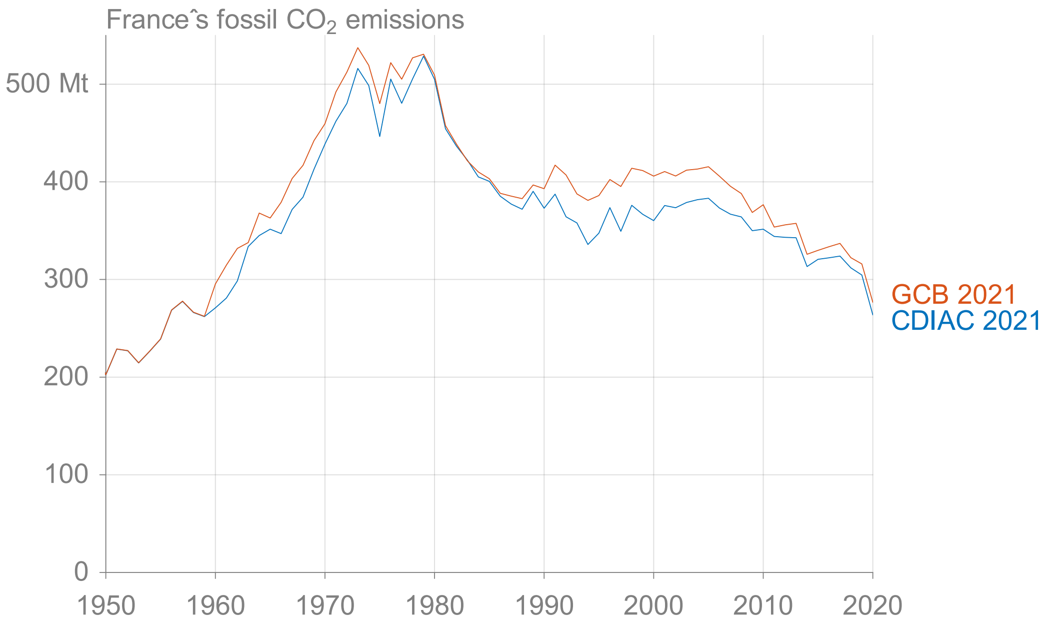

Figure 11: Comparison of France's fossil CO2 emissions reported by CDIAC (Gilfillan et al., 2020) and GCP (this work).

2.2.16. Cement process emissions

Given the demonstrated problems with CDIAC'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 (2021b). 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's cement estimates with those of Andrew (2018). In its 2020 release CDIAC revised its approach, making use of additional data sources from 1990 (Gilfillan and Marland, 2021).

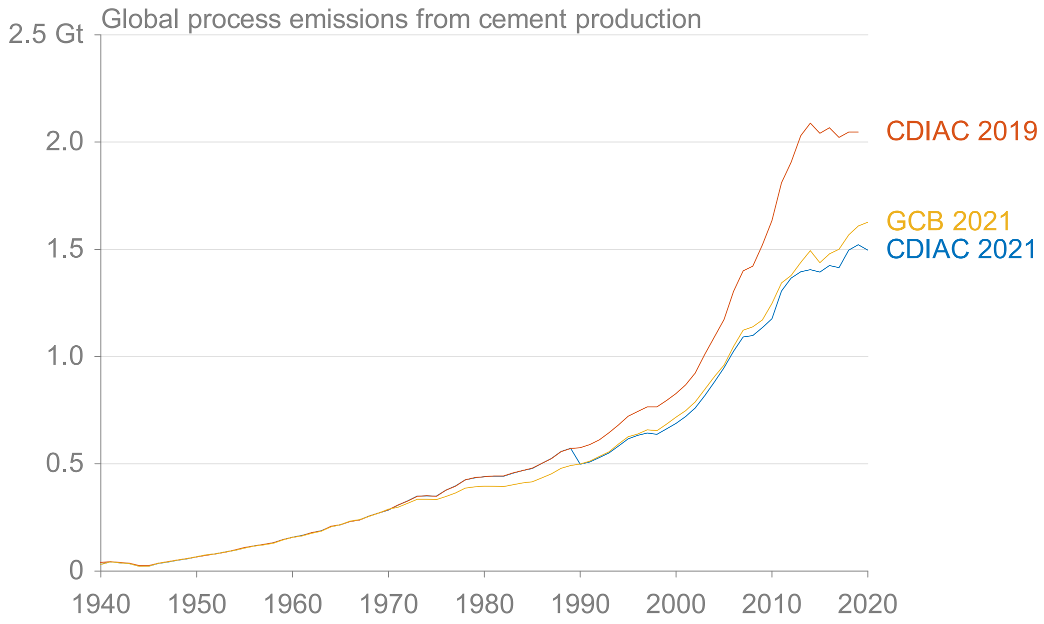

Figure 12: Comparison of global CO_2 process emissions from cement production reported by CDIAC before and after their major methodological revision and from GCP (this work).

2.2.17. Other corrections to CDIAC'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'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'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's data. These negative values arise because of CDIAC'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. 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.

2.2.18. Emissions from international transport in 2020

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

Data from the International Civil Aviation Organization (ICAO) made available as part of special pandemic information release shows that departures of international flights declined by 61% in 2020 compared to the year before (ICAO, 2021), and we have assumed this translates directly to the decline in CO_2 emissions from international flights.

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). We use the figure of 1% for marine bunker emissions.

To maintain the global decline in oil consumption of 9.7% (in energy units) reported by BP for 2020, we make a small adjustment to domestic emissions from oil in those countries for which we have relied on BP growth rates in the year 2020.

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, 2019), and Maddison (2010) before that. The only exception to this currently is Norway, where official data are used from 1750 (SSB, 2021b). UN population data for the most 1-2 years of the dataset are projections rather than observations.

2.4. Continuous country definitions

While CDIAC'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, and Netherland Antilles.

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.

2.5. Source documentation

In this version we attempt for the first time to indicate the data sources used for every value in the dataset. 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 13). 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's estimates showed that the 3EC results had only propagated through the UN energy data CDIAC 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's emissions estimates showed revisions for emissions from coal in China up across all years since 2000, so we switched back again to CDIAC as our data source.

In its 2018 edition, the GCP replaced CDIAC'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 (see Figure 12).

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.

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

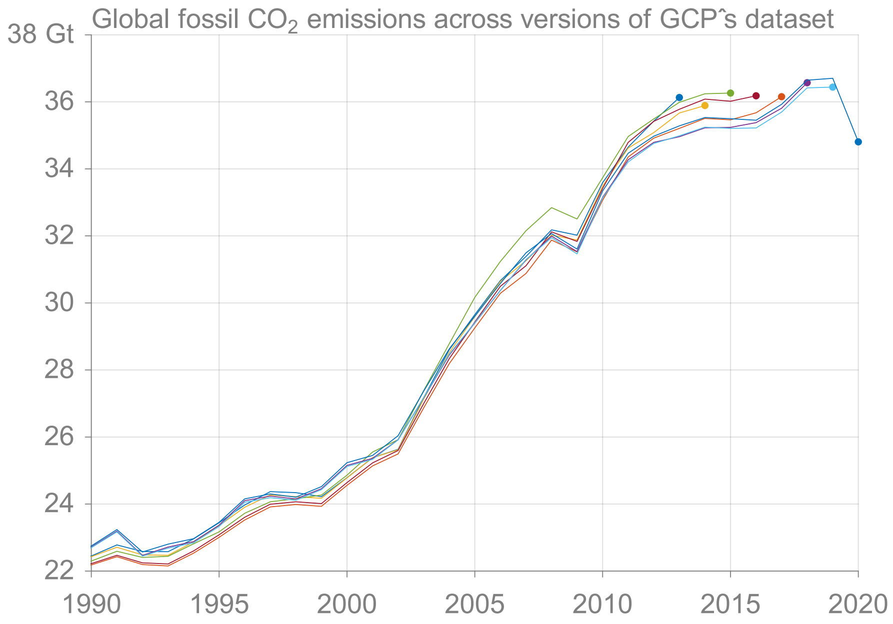

Figure 13: Comparison of global fossil CO_2 emissions from different versions of the GCB dataset. The final data point of each version is always the year before the version number, e.g., the 2021 edition has data through the year 2020 (Y-1).

4. Further Research

4.1. Flaring

For CO_2 emissions from flared natural gas GCP uses CDIAC-FF, which derives its estimates from national reporting to the UN. Estimates derived using newer, satellite-based methods show some deviation at global level (Figure 11) and particularly at national level, and the reasons for this spread are not yet clear. It is known that the estimates derived from satellites are only available in relatively recent years, while earlier years are based on industry estimates, and it is in this earlier period that estimates diverge most.

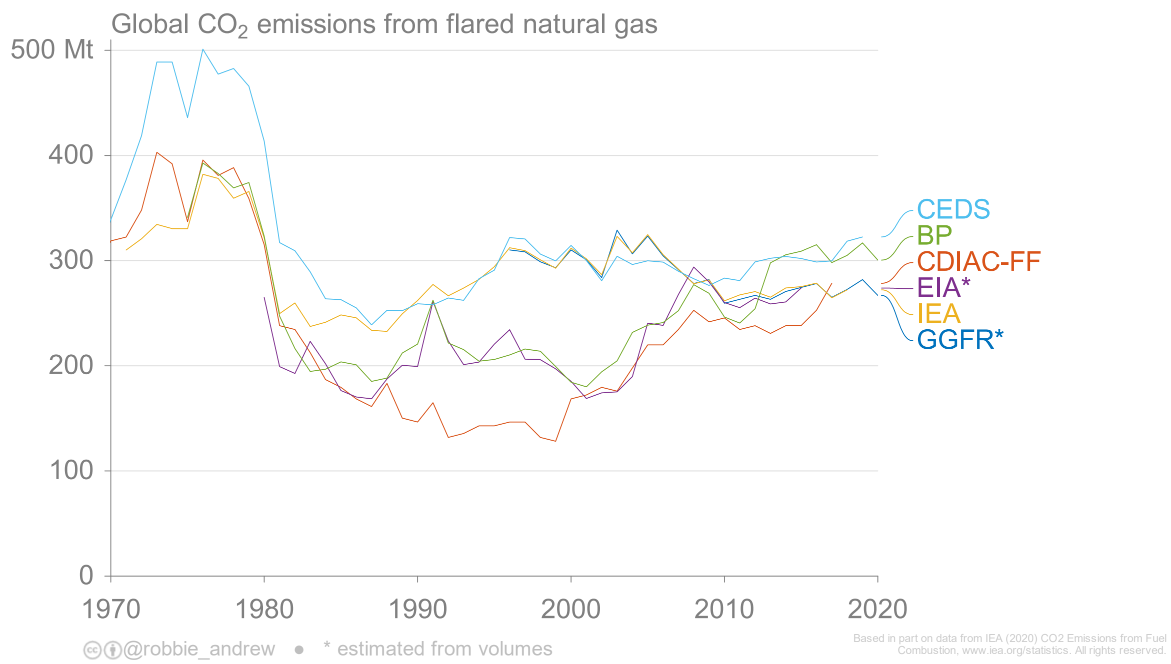

Figure 14: Comparison of estimates of annual global CO_2 emissions from flared natural gas from different sources.

4.2. Extrapolation in final years

Current GCP's extrapolation to the final years (Y-1 for Annex 1 countries and both Y-2 and Y-1 for others) is based on energy growth rates derived from BP 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. 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.

For countries that report to Eurostat, CICERO's other work towards generating monthly emissions estimates from Eurostat's energy data 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.

The Joint Organisation Data Initiative (JODI) dataset collates monthly, high-level data for oil and natural gas for a large number of countries. 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.

4.3. 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 2.2.14), 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.

5. 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 have been significant changes particularly in the 2021 edition, with more use of independent data from countries' own reporting rather than from the country>UN>CDIAC 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.

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Appendix: Change Log

2021v34

- 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 2.2.18).
- Added data from CBS for the Netherlands (see section 2.2.6).