A comprehensive dataset for global, regional and national greenhouse gas emissions by sector 1970-2019

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Abstract

To track progress towards keeping warming well below 2°C, as agreed upon in the Paris Agreement, comprehensive and reliable information on anthropogenic sources of greenhouse gas emissions (GHG) is required. Here we provide a dataset on anthropogenic GHG emissions 1970-2019 with a broad country and sector coverage. We build the dataset from recent releases of the “Emissions Database for Global Atmospheric Research” (EDGAR) for CO₂ emissions from fossil fuel combustion and industry (FFI), CH₄ emissions, N₂O emissions, and fluorinated gases, and use a well-established fast-track method to extend this dataset from 2018 to 2019. We complement this with data on net CO₂ emissions from land use, land-use change and forestry (LULUCF) from three bookkeeping models. We provide an assessment of the uncertainties in each greenhouse gas at the 90% confidence interval (5th-95th percentile) by combining statistical analysis and comparisons of global emissions inventories with an expert judgement informed by the relevant scientific literature. We identify important data gaps: CH₄ and N₂O emissions could be respectively 10-20% higher than reported in EDGAR once all emissions are accounted. F-gas emissions estimates for individual species in EDGARv5 do not align well with atmospheric measurements and the F-gas total exceeds measured concentrations by about 30%. However, EDGAR and official national emission reports under the UNFCCC do not comprehensively cover all relevant F-gas species. Excluded F-gas species such as chlorofluorocarbons (CFCs) or...
hydrochlorofluorocarbons (HCFCs) are larger than the sum of the reported species. GHG emissions in 2019 amounted to 59±6.6 GtCO$_2$eq: CO$_2$ emissions from FFI were 38±3.0 Gt, CO$_2$ from LULUCF 6.6±4.6 Gt, CH$_4$ 11±3.3 GtCO$_2$eq, N$_2$O 2.4±1.5 GtCO$_2$eq and F-gases 1.6±0.49 GtCO$_2$eq. Our analysis of global, anthropogenic GHG emission trends over the past five decades (1970-2019) highlights a pattern of varied, but sustained emissions growth. There is high confidence that global anthropogenic greenhouse gas emissions have increased every decade. Emission growth has been persistent across different (groups of) gases. While CO$_2$ has accounted for almost 75% of the emission growth since 1970 in terms of CO$_2$eq as reported here, the combined F-gases have grown at a faster rate than other GHGs, albeit starting from low levels in 1970. Today, F-gases make a non-negligible contribution to global warming – even though CFCs and HCFCs, regulated under the Montreal Protocol and not included in our estimates, have contributed more. There is further high confidence that global anthropogenic GHG emission levels were higher in 2010-2019 than in any previous decade and GHG emission levels have grown across the most recent decade. While average annual greenhouse gas emissions growth slowed between 2010-2019 compared to 2000-2009, the absolute increase in average decadal GHG emissions from the 2000s to the 2010s has been the largest since the 1970s – and within all human history as suggested by available long-term data. We note considerably higher rates of change in GHG emissions between 2018 and 2019 than for the entire decade 2010-2019, which is numerically comparable with the period of high GHG emissions growth during the 2000s, but we place low confidence in this finding as the majority of the growth is driven by highly uncertain increases in CO$_2$-LULUCF emissions as well as the use of preliminary data and extrapolation methodologies for these most recent years. While there is a growing number of countries today on a sustained emission reduction trajectory, our analysis further reveals that there are no global sectors that show sustained reductions in GHG emissions. We conclude by highlighting that tracking progress in climate policy requires substantial investments in independent GHG emission accounting and monitoring as well as the available national and international statistical infrastructures. The data associated with this article (Minx et al., 2021) can be found at https://doi.org/10.5281/zenodo.5053056.

[NOTE TO REVIEWERS: Data on CO$_2$ emissions from fossil fuel combustion and industry, methane emissions and nitrous oxide emissions are from the most recent EDGARv6 data. As EDGARv6 data is still being compiled for F-gases, this manuscript contains EDGARv5 estimates for these, but we will update to EDGARv6 during the revision process. This procedures has been agreed upon with David Carlson – one of the chief editors of the journal – before manuscript submission]
1 Introduction

By signing the Paris Agreement, countries acknowledged the necessity to keep the most severe climate change risks in check by limiting warming to well below 2°C and pursue efforts to limit warming to 1.5°C (UNFCCC, 2015). This requires rapid and sustained greenhouse gas (GHG) emission reductions towards net zero carbon dioxide (CO₂) emissions well within the 21st century along with deep reductions in non-CO₂ emissions (Rogelj et al., 2015, 2018a). Transparent, comprehensive, consistent, accurate and up-to-date inventories of anthropogenic GHG emissions are crucial to track progress by countries, regions and sectors in moving towards these goals.

However, tracking the recent GHG performance of countries and sectors has been challenging. While there is a growing number of global emissions inventories, only very few of them provide a wide coverage of gases, sectors, activities, and countries or regions that are sufficiently up-to-date to aid discussions in science and policy on progress tracking. Table 1 provides an overview of global emission inventories. Many inventories focus on individual gases and subsets of activities. Few provide sectoral detail and particularly for non-CO₂ GHG emissions there is often a considerable time-lag in reporting. Similarly, GHG emissions reporting under the United Nations Framework Convention on Climate Change (UNFCCC) provides reliable, comprehensive and up-to-date statistics for Annex I countries across all major GHGs, but there remain substantial gaps for non-Annex I countries, which often lack a well-developed statistical infrastructure to provide detailed reports (Janssens-Maenhout et al., 2019).

Here we describe a new, comprehensive dataset for global, regional and national greenhouse gas emissions by sector for 1970-2019. Our focus is on anthropogenic GHG emissions only. We build the dataset from recent releases of the “Emissions Database for Global Atmospheric Research” (EDGAR) for CO₂ emissions from fossil fuel combustion and industry (FFI), CH₄ emissions, N₂O emissions, and fluorinated gases (F-gases). We use a well-established fast-track method to extend this dataset to 2019 (Crippa et al., 2020, 2021). For completeness we add net CO₂ emissions from land use, land-use change and forestry (CO₂-LULUCF) from three bookkeeping models (Gasser et al., 2020; Hansis et al., 2015; Houghton and Nassikas, 2017). We provide an assessment of the uncertainties in each greenhouse gas at the 90% confidence interval (5th-95th percentile) by combining statistical analysis and comparisons of global emissions inventories with an expert judgement informed by the relevant scientific literature.
| Dataset Name                                      | Short Name | Version | Gases                  | Geographic coverage     | Activity split | Time period       | Emission factors | Dependencies                  | Reference                                                                                       | Link                                                                                     |
|--------------------------------------------------|------------|---------|------------------------|-------------------------|------------------|------------------|------------------|------------------|----------------------------------|------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| Emissions Database for Global Atmospheric Research | EDGAR      | 6.0     | CO₂–FFI, CH₄, N₂O     | 208 countries; global   | 5 main sectors     | 1970-2019 for CO₂; 1970-2015 for other GHG | IEA, BP, USGS, IFA, GGFR/N OAA, UNFCCC | (Crippa et al., 2021)            | https://data.jrc.ec.europa.eu/collection/EDGAR                                                                                       |
| Potsdam Real-time Integrated Model for probabilistic Assessment of emissions Paths | PRIMAP-hist | 2.2    | CO₂–FFI, CH₄, N₂O     | All UNFCCC member states, most non-UNFCCC territories | 5 sectors         | 1850-2018        |                  | Andrew (2019), BP, CDIAC, EDGAR, EDGAR-HYDE, FAOSTAT, RCP, UNFCCC | Gütschow et al. (2016, 2019, 2021)                                                                                       | https://www.pik-potsdam.de/paris-reality-check/primap-hist/                                                                                       |
| Community Emissions Data System                   | CEDS        | v_2021_02_05 | SO₂, NOₓ, BC, OC, NH₃, NMVOC, CO, CO₂, CH₄, N₂O | 221 countries          | 60 sectors        | 1750-2019 (1970-2019 for CH₄ and N₂O) | ECLIPSE V5a combustion emission factors, IMOGHG v4 shipping emission factors, country specific data | IEA, BP, ECLIPSE, EDGAR, UNFCCC and other country inventory data | Hoesly et al. (2018); McDuffie et al. (2020); O’Rourke et al. (2021)                                                                                       | http://www.globalchange.umd.edu/ceds/                                                                                                        |
| UNFCCC: Annex I Party GHG Inventory Submissions   |            | 2021    | CO₂, CH₄, N₂O, NOₓ, CO, NMVOC, SO₂ | Parties included in Annex I to the Convention on Energy, industry, agriculture, LULUCF, waste |                | 1990-2018        |                  | Country inventory submissions                                      | https:// unfccc.int/ghg-inventories-annex-i-parties/2021                                                                                           |
| Global Carbon Budget                              | GCP        | 2020    | CO₂–FFI, CO₂–LULUCF   | Global, 259 countries for FFI | 5 main categories | CO₂-LULUCF: 1850-2019 CO₂-FFI: 1750-2019 | CDIAC, UNFCCC, Andrew (2019), BP, and other country inventory data; for LULUCF FAO/FRA and LUH2 land-use | Friedlingstein et al. (2019b, 2020)                                                                                           | https://doi.org/10.18180/GCP-2020                                                                                                      |
| Forcing Data                                      | Source                                                                                               |
|--------------------------------------------------|------------------------------------------------------------------------------------------------------|
| Global, Regional, and National Fossil-Fuel CO2 Emissions | CDIAC-FF V2017 CO2-FFI 259 countries, global 5 main categories 1751-2017 Gilfillan et al. (2020) https://energy.appstate.edu/research/work-areas/cdiac-appstate |
| Energy Information Administration International Energy Statistics | EIA CO2-FFI 230 countries, global 3 fuel types 1980-2018; 1949-2018 (global)                          |
| BP Statistical Review of World Energy             | BP CO2-FFI 2020 | 69th edition 108 countries, 7 regions 8 activities, 3 fossil and 3 other fuel types 1965-2019 IPCC default emission factors https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html |
| International Energy Agency CO2 Emissions from Fuel Combustion | IEA CO2-FFI 190 countries 3 fossil fuels, 6 sectors 1971-2019; OECD: 1960-2019 2006 GLs for National Greenhouse Gas Inventories https://www.worldbank.org/data/program/co2-emissions-from-fuel-combustion-2019-highlights |
| PKU-FUEL                                          | CO2, CO, PM2.5, PM10, TSP, BC, OC, SO2, NOx, NH3, PAHs 6 sectors, 5 fuel types, 1960-2014 http://inventory.pku.edu.cn/ |
| Carbon Monitor                                    | CO2-FFI 11 countries, global 6 sectors 2019- EIA, EDGAR, GCP Liu et al. (2020) https://carbonmonitor.org/ |
| Bookkeeping of land-use emissions                 | BLUE CO2-LULUCF 1500-2012 LUH2 land-use forcing data Hansis et al. (2015) https://doi.org/10.18160/GCP-2020 |
| OSCAR – an Earth system                           | OSCAR CO2-LULUCF 1750-2010 FAO/FRA and LUH2 land-use Gasser et al. (2017, 2020) https://doi.org/10.18160/GCP-2020 |
| Source                                 | Model                                                                 | Species            | Region/Type                          | Time Period | Reference                                      | Website                                                                |
|---------------------------------------|-----------------------------------------------------------------------|--------------------|--------------------------------------|-------------|-----------------------------------------------|-------------------------------------------------------------------------|
| Houghton and Nassikas                 | Bookkeeping Model                                                     | CO₂-LULUCF         | 160/GCP-2020v                        | 1850-2015   | Houghton and Nassikas (2017)                  | https://doi.org/10.18160/GCP-2020v                                     |
| The Greenhouse gas – Air pollution I Nteractions and Synergies Model | GAINS                                                                 | CO₂, CH₄, N₂O, F-gases | 83 countries/regions                 | 1980-2016   | Höglund-Isaksson (2012)                       |                                                                         |
| EPA-2020: Greenhouse gas emission inventory | US-EPA                                                                | CO₂, CH₄, N₂O, F-gases | USA 6 sectors                        | 1990-2019   | EPA (2021)                                    | https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019 |
| GCP – global nitrous oxide budget     | GCP/INI                                                                | N₂O                | 10 land regions and 3 oceanic regions | 1990-2017   | PRIMAP-hist                                   | http://www.fao.org/FAOSTAT/en/#data/EM/metadata                        |
| FAOSTAT inventory                     |                                                                       | CO₂, CH₄, N₂O, F-gases | Global (198 countries)                | 1990-2017   | PRIMAP-hist                                   | http://www.fao.org/FAOSTAT/en/#data/EM/metadata                        |
| Fire Inventory from NCAR              | FINN                                                                  | CO₂, CH₄, N₂O      | Global                               |             | Wiedinmyer et al. (2011)                     |                                                                         |
| Global fire assimilation system       | GFAS                                                                  | CO₂, CH₄, N₂O      | Global                               |             | Kaiser et al. (2012)                         |                                                                         |
| Global fire emissions database        | GFED                                                                  | CO₂, CH₄, N₂O      | Global                               |             | Giglio et al. (2013)                         |                                                                         |
| Quick fire emissions dataset          | QFED                                                                  | CO₂, CH₄, N₂O      | Global                               |             | Darmenov and da Silva (2015)                 |                                                                         |
2 Methods and Data

2.1 Overview

Our dataset provides a comprehensive set of estimates for global anthropogenic GHG emissions disaggregated by 30 economic sectors and 226 countries. The focus of the data is on anthropogenic GHG emissions originally regulated under the Kyoto Protocol: natural sources and sinks are not considered, and nor are ozone depleting substances regulated under the Montreal Protocol such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). We distinguish five groups of gases: (1) CO$_2$ emissions from fossil fuel combustion and industry (CO$_2$-FFI); (2) CO$_2$ emissions from land use, land-use change and forestry (CO$_2$-LULUCF); (3) methane emissions (CH$_4$); (4) nitrous oxide emissions (N$_2$O); (5) the group of fluorinated gases (F-gases) comprising hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) as well as sulphur hexafluoride (SF6). We do not cover NF$_3$ emissions [NOTE TO REVIEWERS: Our update of F-gas emissions to EDGAR v6 will also add NF3 emissions to our data], which are also covered under the Paris Agreement. We provide and analyse the GHG emissions data both in native units as well as in CO$_2$-equivalents (see Section 3.7) as commonly done in wide parts of the climate change mitigation community using global warming potentials with a 100 year time horizon from the IPCC Fifth Assessment Report (Myhre et al., 2013). We briefly discuss the impact of alternative metric choices in tracking aggregated GHG emissions over the past few decades and compare the emissions with estimated anthropogenic warming.

We report the annual growth rate in emissions $E$ for adjacent years (in percent per year) by calculating the difference between the two years and then normalizing to the emissions in the first year: \($\frac{(E_{(t+1)}-E_0)}{E_0}\times100$\). We apply a leap-year adjustment where relevant to ensure valid interpretations of annual growth rates. This affects the growth rate by about 0.3%yr$^{-1}$ (1/366) and causes calculated growth rates to go up by approximately 0.3% if the first year is a leap year and down by 0.3% if the second year is a leap year. We calculate the relative growth rate in percent per year for multi-year periods (e.g. a decade) by fitting a linear trend to the logarithmic transformation of $E$ across time (see Friedlingstein et al., 2020).

Our dataset draws from three underlying sources: (1) the full EDGARv6 release for CO$_2$-FFI as well as non-CO$_2$ GHGs covering the time period 1970-2018 (Crippa et al., 2021). Note that currently F-gas data from EDGARv6 is still being prepared. In the meantime, we use EDGARv5 data covering the time period 1970-2015 (Crippa et al., 2019); (2) EDGAR fast-track extensions for CO$_2$-FFI, CH$_4$ and N$_2$O emissions for 2019 as well as 2016-2019 for F-gas emissions based on Olivier et al. (2005) and Crippa et al. (2020) [NOTE TO REVIEWERS: F-gas emissions in EDGARv6 are currently being revised and will be included in the revised version of this manuscript. F-gases will then also have a fast-track extension from 2018 to 2019]; (3) CO$_2$-LULUCF as the average of three bookkeeping models, consistent with the approach of the global carbon project (Friedlingstein et al., 2020).
Table 2, sectoral detail is organised along five major economic sectors as is common in IPCC reports on climate change mitigation (IPCC, 2014): energy supply, buildings, transport, industry as well as Agriculture, Forestry and Other Land-Use Changes (AFOLU). We devise a classification for assigning our 226 countries to regions, combining the standard Annex I/non-Annex I distinction with geographical location. We provide other common regional classifications from the UN and the World Bank as part of the supplementary files. The dataset including the sector and region classification can be found at https://doi.org/10.5281/zenodo.5053056.

Table 2 – Overview of the two-level sector aggregation with reference to assigned source/sink categories conforming to the IPCC reporting guidelines (IPCC, 2006, 2019) as well as relevant greenhouse gases. Note that EDGAR v6 distinguishes biogenic CO₂ and CH₄ sources with a “bio” label, with all other sectors “fossil” by default.

| Sector | Sub-sector | IPCC (2006) | Gases |
|--------|------------|-------------|-------|
| AFOLU (Agriculture, Forestry and Other Land-Use Changes) | Biomass burning | 3.C.1.b (bio) | CH₄, N₂O |
| | Enteric Fermentation | 3.A.1.a (fossil), 3.A.1.a.ii (fossil), 3.A.1.b (fossil), 3.A.1.c (fossil), 3.A.1.d (fossil), 3.A.1.e (fossil), 3.A.1.f (fossil), 3.A.1.g (fossil), 3.A.1.h (fossil) | CH₄ |
| | Managed soils and pasture | 3.C.4 (fossil), 3.C.5 (fossil), 3.C.6 (fossil), 3.C.3 (fossil), 3.C.2 (fossil) | CO₂, N₂O |
| | Manure management | 3.A.2.a.i (fossil), 3.A.2.a.ii (fossil), 3.A.2.b (fossil), 3.A.2.c (fossil), 3.A.2.i (fossil), 3.A.2.d (fossil), 3.A.2.e (fossil), 3.A.2.f (fossil), 3.A.2.g (fossil), 3.A.2.h (fossil) | CH₄, N₂O |
| | Rice cultivation | 3.C.7 (fossil) | CH₄ |
| | Synthetic fertilizer application | 3.C.4 (fossil) | N₂O |
| | Land-use change | | CO₂ |
| Buildings | Non-CO₂ (all buildings) | 2.F.3 (fossil), 2.F.4 (fossil), 2.G.2.c (fossil) | c-C4F₈, C4F₁₀, CF₄, HFC-134a, SF₆ |
| | Non-residential | 1.A.4.a (bio), 1.A.4.a (fossil) | CO₂, CH₄, N₂O |
| | Residential | 1.A.4.b (bio), 1.A.4.b (fossil) | CO₂, CH₄, N₂O |
| Energy systems | Biomass energy systems | 1.A.1.a.i (bio), 1.A.1.a.ii (bio), 1.A.1.a.iii (bio), 1.A.1.a (bio), 1.A.1.c.ii (bio), 1.A.1.c.ii (bio), 1.A.1.c.i (bio), 1.A.4.c.i (bio), 1.A.5.a (bio), 1.B.1.c (bio), 1.B.2.a.iii.2 (bio) | CH₄, N₂O |
| | Coal mining & heat & Oil and gas emissions | 1.B.1.c (fossil) | CO₂, CH₄ |
| | Electricity & gas emissions | 1.B.1.a (fossil), 1.B.1.a (fossil), 1.B.1.a (fossil) | CO₂, CH₄, N₂O |
| | Other energy systems | 1.B.2.a.ii.2 (fossil), 1.B.2.a.ii.3 (fossil), 1.B.2.a.ii.4 (fossil), 1.B.2.b.ii.2 (fossil), 1.B.2.b.ii.4 (fossil), 1.B.2.b.ii.5 (fossil), 1.B.2.b.ii.3 (fossil), 1.B.2.b.ii (fossil), 1.B.2.a.ii (fossil) | CO₂, CH₄, N₂O |
| | Petroleum refining | 1.A.1.b (fossil) | CO₂, CH₄, N₂O |
Industry |  | Cement | 2.A.1 (fossil) | CO2 |
--- | --- | --- | --- | --- |
 |  |  | 1.A.2.c (bio), 1.A.2.c (fossil), 2.A.2 (fossil), 2.A.4.d (fossil), 2.A.4.b (fossil), 2.A.3 (fossil), 2.B.1 (fossil), 2.B.2 (fossil), 2.B.3 (fossil), 2.B.5 (fossil), 2.B.8.f (fossil), 2.B.8.b (fossil), 2.B.8.c (fossil), 2.B.8.a (fossil), 2.B.4 (fossil), 2.B.6 (fossil), 2.B.9.b (fossil), 2.D.3 (fossil), 2.G.3.a (fossil), 2.G.3.b (fossil) | CO2, CH4, N2O, HFC-23, SF6 |
 |  |  | 1.A.2.a (bio), 1.A.2.a (fossil), 1.A.2.b (bio), 1.A.2.b (fossil), 1.B.1.c (fossil), 2.C.1 (fossil), 2.C.2 (fossil), 2.C.3 (fossil), 2.C.4 (fossil), 2.C.5 (fossil), 2.C.6 (fossil) | CO2, CH4, N2O, C2F6, CF4, SF6 |
 |  |  | 1.A.2.d (bio), 1.A.2.d (fossil), 1.A.2.e (bio), 1.A.2.e (fossil), 1.A.2.f (fossil), 1.A.2.k (fossil), 1.A.2.i (fossil), 1.A.5.b.iii (fossil), 2.F.1.a (fossil), 2.F.2 (fossil), 2.F.5 (fossil), 2.E.1 (fossil), 2.E.2 (fossil), 2.E.3 (fossil), 2.G.1.a (fossil), 2.G.2.c (fossil), 2.G.2.b (fossil), 2.G.2.a (fossil), 2.D.1 (fossil), 5.A (fossil) | CO2, CH4, N2O, C2F6, CF4, SF6 |
 |  |  | 4.A.1 (fossil), 4.D.2 (fossil), 4.D.1 (fossil), 4.C.1 (fossil), 4.C.2 (bio), 4.C.2 (fossil), 4.B (fossil) | CO2, CH4, N2O |

| Transport | Domestic Aviation | 1.A.3.a.ii (fossil) | CO2, CH4, N2O |
| --- | --- | --- | --- |
| Inland Shipping | 1.A.3.d.ii (bio), 1.A.3.d.ii (fossil) | CO2, CH4, N2O |
| International Aviation | 1.A.3.a.i (fossil) | CO2, CH4, N2O |
| International Shipping | 1.A.3.d.i (bio), 1.A.3.d.i (fossil) | CO2, CH4, N2O |
| Other (transport) | 1.A.3.e.i (bio), 1.A.3.e.i (fossil), 1.A.4.c.ii (fossil), 1.A.4.c.iii (bio), 1.A.4.c.iii (fossil) | CO2, CH4, N2O |
| Rail | 1.A.3.c (bio), 1.A.3.c (fossil) | CO2, CH4, N2O |
| Road | 1.A.3.b (bio), 1.A.3.b (fossil), 2.G.2.c (fossil) | CO2, CH4, N2O, SF6 |

### 2.2 The Emissions Database for Global Atmospheric Research (EDGAR)

EDGAR emission estimates included in our dataset are derived from two methodologies: a) full bottom-up emission inventory data; b) fast-track emission inventory data imputed from incomplete input data. As described in Janssens-Maenhout et al. (2019), the EDGAR bottom-up emission inventory estimates are calculated from international activity data and emission factors following the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) - updated according to the latest scientific knowledge. Emissions (EMs) from a given sector $i$ in a country $C$ accumulated during a year $t$ for a chemical compound $x$ are calculated with the country-specific activity data (AD), quantifying the activity in sector $i$, with the mix of $j$ technologies (TECH) and with the mix of $k$ (end-of-pipe) abatement measures (EOP) installed with the share $k$ for each technology $j$, the emission rate with an uncontrolled emission factor (EF) for each sector $i$ and technology $j$ and relative reduction (RED) by abatement measure $k$, as summarised in the following formula:
\[ EM_i(C, t, x) = \sum_{j, k} [AD_i(C, t) \cdot TECH_{i,j}(C, t) \cdot EOP_{i,j,k}(C, t) \cdot EF_{i,j}(C, t, x) \cdot (1 - RED_{i,j,k}(C, t, x))] \]

The activity data are sector dependent and vary from fuel combustion in energy units (TJ) of a particular fuel type, to the amount (ton) of products manufactured, or to the number of animals or the area (hectares) or yield (ton) of cultivated crops. The technology mixes, (uncontrolled) emission factors and end-of-pipe measures are determined at different levels: country-specific, regional, country group (e.g. Annex I/non-Annex I), or global. Technology-specific emission factors are used to enable an IPCC tier-2 approach, taking into account the different management and /technology processes or infrastructures (e.g., different distribution networks) under specific “technologies”, and modelling explicitly abatements/ emission reductions, e.g. the CH4 recovery from coal mine gas at country level under the “end-of-pipe measures”. As with national inventories, emissions are accounted over a period of one calendar year in the country in which they took place (i.e. a territorial accounting principle) (IPCC, 2006, 2019). A full description of data sources and methodology for EDGARv6 is provided in Crippa et al. (2021).

Extensions to 2019 are derived using a “fast-track methodology”, which is designed to update full EDGAR inventories to more recent years based on less information (Crippa et al., 2020; Olivier et al., 2005; Olivier and Peters, 2020). The underlying idea is to extrapolate emissions trends based on observed activity trends in key sectors. For CO2-FFI emissions, the fast track estimates were based on the latest BP coal, oil and natural gas consumption data (BP, 2019). Updates for cement, lime, ammonia and ferroalloys production are based on US Geological Survey statistics, urea production and consumption on statistics from the International Fertilizer Association, gas used from flaring on data from the Global Gas Flaring Reduction Partnership, steel production on statistics from the World Steel Association, and cement clinker production on UNFCCC data. For methane and nitrous oxide emissions, fast-track extensions are based on detailed agricultural statistics from FAO (CH4 and N2O), fuel production and transmission statistics from IEA and BP (CH4) as well as UNFCCC-CRF data for Annex I countries on coal production (CH4 recovery) and the production of chemicals (N2O abatement). Finally, for F-gas emissions, a more extensive fast-track extension covering 2016-2019 was undertaken. For Annex I countries, these fast-track extensions were based on the most recent national emission inventories, submitted under the UNFCCC (up to 2018). For all remaining countries and years, simple extrapolation was used given the absence of international statistics. Available fast-track data is from EDGARv5, which we link to the full EDGARv6 release by calculating the county and sector specific emissions growth between 2018 and 2019 and multiplying it with the 2018 values in our data.

2.3 Accounting for CO2 emissions Land Use, Land-Use Change and Forestry (CO2-LULUCF)

We consider all fluxes of CO2 from land use, land-use change and forestry. This includes CO2 fluxes from the clearing of forests and other natural vegetation (by anthropogenic fire and/or clear-cut), afforestation, logging and forest degradation
(including harvest activity), shifting cultivation (cycles of forest clearing for agriculture, then abandonment), and regrowth of forests and other natural vegetation following wood harvest or abandonment of agriculture, and emissions from peat burning and drainage. Some of these activities lead to emissions of CO$_2$ to the atmosphere, while others lead to CO$_2$ sinks. CO$_2$-LULUCF therefore is the net sum of emissions and removals from all human-induced land use changes and land management. Note that CO$_2$-LULUCF is referred to as (net) land-use change emissions, ELUC, in the context of the global carbon budget (Friedlingstein et al., 2020). Agriculture per se, apart from conversions between different agricultural types, does not lead to substantial CO$_2$ emissions as compared to land-use changes such as clearing or regrowth of natural vegetation. Therefore, CO$_2$ fluxes in the AFOLU sector refer mostly to forestry and other land use (changes), while the agricultural part of the sector is covered by CH$_4$ and N$_2$O emissions.

Since in reality anthropogenic CO$_2$-LULUCF emissions co-occur with natural CO$_2$ fluxes in the terrestrial biosphere, models have to be used to distinguish anthropogenic and natural fluxes (Friedlingstein et al., 2020). CO$_2$-LULUCF as reported here is calculated via a bookkeeping approach, as originally proposed by Houghton et al. (2003), tracking carbon stored in vegetation and soils before and after land-use change. Response curves are derived from literature and observations to describe the temporal evolution of the decay and regrowth of vegetation and soil carbon pools for different ecosystems and land use transitions, including product pools of different lifetimes. These dynamics distinguish bookkeeping models from the common approach of estimating "committed emissions" (assigning all present and future emissions to the time of the land use change event), which is frequently derived from remotely-sensed land use area or biomass observations (Ramankutty et al., 2007).

Most bookkeeping models also represent the long-term degradation of primary forest as lowered standing vegetation and soil carbon stocks in secondary forests, and include forest management practices such as wood harvesting.

Following the approach taken by the global carbon budget (Friedlingstein et al., 2020), we take the average of three bookkeeping estimates: the bookkeeping of land use emissions model, BLUE (Hansis et al., 2015), H&N (Houghton and Nassikas, 2017), and OSCAR (Gasser et al., 2020). Key differences across these estimates, including land-use forcing, are summarised in Table 4. Since bookkeeping models do not include emissions from organic soils, emissions from peat fires and peat drainage are added from external datasets: Peat burning is based on the Global Fire Emission Database (GFED4s; (van der Werf et al., 2017)) and introduces large interannual variability to the CO$_2$-LULUCF emissions due to synergies of land-use and climate variability particularly in Southeast Asia, strongly noticeable during El-Niño events such as 1997. Peat drainage is based on estimates by Hooijer et al. (2010) for Indonesia and Malaysia in H&N, and added to BLUE and OSCAR from the global FAO data on organic soils emissions from croplands and grasslands (Conchedda and Tubiello, 2020).
3. Uncertainties in GHG emission estimates

Estimates of historic GHG emissions – CO₂, CH₄, N₂O and F-gases – are uncertain to different degrees. Assessing and reporting uncertainties is crucial in order to understand whether available estimates are sufficiently accurate to answer, for example, whether GHG emissions are still rising, or if a country has achieved an emission reduction goal (Marland, 2008). These uncertainties can be of a scientific nature, such as when a process is not sufficiently understood. They also arise from incomplete or unknown parameter information (activity data, emission factors etc.), as well as estimation uncertainties from imperfect modelling techniques. There are at least three major ways to examine uncertainties in emission estimates (Marland et al., 2009): 1) by comparing estimates made by independent methods and observations (e.g. comparing top-down vs bottom-up estimates; modelling against remote sensing data) (Petrescu et al., 2020c, 2020a; Saunois et al., 2020; Tian et al., 2020); 2) by comparing estimates from multiple sources and understanding sources of variation (Andres et al., 2012; Andrew, 2020a; Ciais et al., 2021; Macknick, 2011); 3) by evaluating multiple estimates from a single source (e.g. Hoesly and Smith, 2018) including approaches such as uncertainty ranges estimated through statistical sampling across parameter values, applied for example at the country or sectoral level (e.g. Andres et al., 2014; Monni et al., 2007; Solazzo et al., 2021), or to spatially distributed emissions (Tian et al., 2019). This section assesses the relevant peer-reviewed literature on uncertainties in historic GHG emission estimates and places an expert judgement on the uncertainties for the different (groups of) GHGs.

Uncertainty estimates can be rather different depending on the method chosen. For example, the range of estimates from multiple sources is bounded by their interdependency; they can be lower than true structural plus parameter uncertainty estimates or than estimates made by independent methods. In particular it is important to account for potential bias in estimates, which can result from using common methodological or parameter assumptions across estimates, or from missing sources, which can result in a systemic bias in emission estimates (see N₂O discussion below). Independent top-down observational constraints are, therefore, particularly useful to bound total emission estimates (Petrescu et al., 2020c, 2020b).

Solazzo et al. (2021) evaluated the uncertainty of the EDGAR’s source categories and their totals for all the main GHGs (CO₂, FFI, CH₄, N₂O). The study is based on the propagation of the uncertainty associated with input parameters (activity data and emission factors) as estimated by expert judgement (tier-1) and complied by IPCC (2006, 2019). A key methodological challenge is determining how well uncertain parameters are correlated between sectors, countries, and regions. The more highly correlated parameters (e.g. emission factors) are across scales, the higher the resulting overall uncertainty estimate. Solazzo et al. (2020) assume full covariance between same source categories where similar assumptions are being used, and independence otherwise. For example, they assume full covariance where the same emission factor is used between countries or sectors, while assuming independence where country-specific emission factors are used. This strikes a balance between extreme assumptions (full independence or full covariance in all cases) that are likely unrealistic, but still leans towards higher uncertainty estimates. When aggregating emission sources, assuming covariance increases the resulting uncertainty estimate.
Uncertainties calculated with this methodology tend to be higher than the range of values from ensemble of dependant inventories (Saunois et al., 2016, 2020). The uncertainty of emission estimates derived from ensembles of gridded results from bio-physical models (Tian et al., 2018) adds an additional dimension of spatial variability, and is therefore not directly comparable with aggregate country or regional uncertainty, estimated with the methods discussed above.

We adopt a 90% confidence interval (5\textsuperscript{th}-95\textsuperscript{th} percentile) to report the uncertainties in our GHG emissions estimates, i.e., there is a 90\% likelihood that the true value will be within the provided range if the errors have a Gaussian distribution, and no bias is assumed. This is in line with previous reporting in IPCC AR5 (Blanco G. et al., 2014; Ciais et al., 2014). The uncertainties reported here combine statistical analysis, comparisons of global emissions inventories and expert judgement of the likelihood of results lying outside this range, rooted in an understanding gained from the relevant literature. At times, we also use a qualitative assessment of confidence levels to characterize the annual estimates from each term based on the type, amount, quality, and consistency of the evidence as defined by the IPCC (IPCC, 2014).

### 3.1 CO\textsubscript{2} emissions from fossil fuels and industrial processes

Several studies have compared estimates of annual CO\textsubscript{2}-FFI emissions from different global inventories (Andres et al., 2012; Andrew, 2020a; Gütschow et al., 2016; Janssens-Maenhout et al., 2019; Macknick, 2011; Petrescu et al., 2020c). However, estimates are not fully independent as they all ultimately rely on many of the same data sources. For example, all global inventories use one of four global energy datasets to estimate CO\textsubscript{2} emissions from energy use, and these energy datasets themselves all rely on the same national energy statistics, with few exceptions (Andrew, 2020a). Divergence between these estimates (see Figure 1) are mainly related to differences in the estimation methodology, conversion factors, emission coefficients, assumptions about combustion efficiency, and calculation errors (Andrew, 2020a; Marland et al., 2009). Key differences for nine global datasets are highlighted in...
Table 3 (see also Table 1 for further information on the inventories). Another major source of divergence between datasets is differences in their respective system boundaries (Andres et al., 2012; Andrew, 2020a; Macknick, 2011). Hence, differences across CO$_2$-FFI emissions estimates do not reflect full uncertainty due to source data dependencies. At the same time, the observed range across estimates from different databases exaggerates uncertainty, to the extent that they largely originate in system boundary differences (Andrew, 2020a; Macknick, 2011).
Table 3 - System boundaries and other key features of global FFI-\(\text{CO}_2\) emissions datasets. Comparison of some important general characteristics of nine emissions datasets, with green indicating a characteristic that might be considered a strength. Columns four to six refer to \(\text{CO}_2\) emission estimates for industrial processes and product use. Since all datasets are under development, these details are subject to change. Further information on the individual inventories can be found in Table 1. Based on Andrew (Andrew, 2020a)

|            | Primary source | Uses IPCC emission factors | Includes venting & flaring | Includes cement | Includes other carbonates | Non-fuel use based on | Reports bunkers separately | By fuel type | By sector | Includes official estimates |
|------------|----------------|---------------------------|---------------------------|----------------|---------------------------|-----------------------|---------------------------|-------------|----------|--------------------------|
| CDIAC      | yes            | no                        | yes                       | yes            | no                        | national data         | yes                       | yes         | no       | no                       |
| BP         | yes            | yes                       | no                        | no             | no                        | national data         | no                       | no          | no       | no                       |
| IEA        | yes            | yes                       | no                        | no             | no                        | national data         | yes                       | yes         | yes      | no                       |
| EDGAR      | yes            | yes                       | yes                       | yes            | yes                       | national data         | yes                       | no          | yes      | no                       |
| EIA        | yes            | no                        | yes                       | no             | no                        | US data               | no                       | yes         | no       | no                       |
| GCP        | partial        | no                        | yes                       | yes            | partial                   | national data         | yes                       | yes         | no       | yes                      |
| CEDS       | mostly         | no                        | yes                       | yes            | yes                       | national data         | yes                       | yes         | yes      | yes                      |
| PRIMAP-hist| no             | no                        | yes                       | yes            | yes                       | national data         | yes                       | no          | yes      | yes                      |
| UNFCCC CRFs| yes            | partial                   | yes                       | yes            | yes                       | national data         | yes                       | yes         | yes      | yes                      |

Across global inventories, mean global annual \(\text{CO}_2\)-FFI emissions track at 34.4±2 Gt\(\text{CO}_2\) in 2014, reflecting a variability of about ±5.4% (Figure 1). However, this variability is almost halved when system boundaries are harmonised (Andrew, 2020a). EDGARv6 \(\text{CO}_2\)-FFI emissions as used in this report track at the top of the range as shown in Figure 1. This is partly due to the comprehensive system boundaries of EDGAR, but also due to the assumption of 100% oxidation of combusted fuels as per IPCC default assumptions. Once system boundaries are harmonised EDGAR continues to track at the upper end of the range, but no longer at the top. EDGAR \(\text{CO}_2\) FFI estimates are further well-aligned with emission inventories submitted by Annex I countries to the UNFCCC – even though some variation can occur for individual countries (Andrew, 2020a). Differences in FFI-\(\text{CO}_2\) emissions across different version of the EDGAR dataset are shown in the Supplementary Material (see Fig. SM-1).
Uncertainties in CO₂-FFI emissions arise from the combination of uncertainty in activity data and uncertainties in emission factors including assumptions for combustion completeness and non-combustion uses. CO₂-FFI emissions estimates are largely derived from energy consumption activity data, where data uncertainties are comparatively small due to well established statistical monitoring systems, although there are larger uncertainties in some countries and time periods (Andres et al., 2012; Andrew, 2020a; Ballantyne et al., 2015; Janssens-Maenhout et al., 2019; Macknick, 2011). Most of the underlying uncertainties are systematic and related to underlying biases in the energy statistics and accounting methods used (Friedlingstein et al., 2020). Uncertainties are lower for fuels with relatively uniform properties such as natural gas, oil or gasoline and higher for fuels with more diverse properties, such as coal (IPCC 2006; Blanco G. et al. 2014). Uncertainties in CO₂ emissions estimates from industrial processes, i.e. non-combustive oxidation of fossil fuels and decomposition of carbonates, are higher than for fossil fuel combustion. At the same time, products such as cement also take up carbon over their life cycle, which are often not fully considered in carbon balances (Guo et al., 2021; Sanjuán et al., 2020; Xi et al., 2016). However, recent versions of the global carbon budget include specific estimates for the cement carbonation sink and estimate average annual CO₂ uptake at 0.70 GtCO₂ for 2010-2019 (Friedlingstein et al., 2020).

Uncertainties of energy consumption data (and, therefore, CO₂-FFI emissions) are generally higher for the first year of their publication when less data is available to constrain estimates. In the BP energy statistics, 70% of data points are adjusted by an average of 1.3% of a country’s total fossil fuel use in the subsequent year with further more modest revisions later on (Hoesly and Smith, 2018). Uncertainties are also higher for developing countries, where statistical reporting systems do not have the same level of maturity as in many industrialised countries (Andres et al., 2012; Andrew, 2020b; Friedlingstein et al., 2019, 2020; Gregg et al., 2008; Guan et al., 2012; Janssens-Maenhout et al., 2019; Korsbakken et al., 2016; Marland, 2008).

Example estimates of uncertainties for CO₂ emissions from fossil fuel combustion at the 95% confidence interval are ±3-5% for the U.S., ±15 - ±20% for China and ±50% or more for countries with poorly developed or maintained statistical infrastructure (Andres et al., 2012; Gregg et al., 2008; Marland et al., 1999). However, these customary country groupings do not always predict the extent to which a country’s energy data has undergone historical revisions (Hoesly and Smith, 2018). Uncertainties in CO₂-FFI emissions before the 1970s are higher than for more recent estimates. Over the last two to three decades uncertainties have increased again because of increased production in some developing countries with less rigorous statistics and more uncertain fuel properties (Ballantyne et al., 2015; Friedlingstein et al., 2020; Marland et al., 2009).

The global carbon project (Friedlingstein et al., 2019, 2020; Le Quéré et al., 2018) assesses uncertainties in global anthropogenic CO₂-FFI emissions estimates within one standard deviation (1σ) as ±5% (±10% at 2σ). This is broadly consistent with the ±8.4% uncertainty estimate for CDIAC (Andres et al., 2014) as well as the ±7 - ±9% uncertainty estimate for EDGARv4.3.2 and v5 (Janssens-Maenhout et al., 2019; Solazzo et al., 2021) at 2σ. It remains at the higher end of the ±5% - ±10% range provided by Ballantyne et al. (2015). Consistent with the above uncertainty assessments, we present uncertainties...
for global anthropogenic CO$_2$ emissions at ±8% for a 90% confidence interval in line with IPCC AR5 and the UN emissions gap report (Blanco G. et al., 2014; UNEP, 2020).

3.2 Anthropogenic CO$_2$ emissions from land use, land use change and forestry (CO$_2$-LULUCF)

CO$_2$-LULUCF emissions are drawn from three global bookkeeping models. For 1990-2019, average net CO$_2$-LULUCF emissions are estimated at 6.1, 4.3, and 5.6 GtCO$_2$ yr$^{-1}$ for BLUE, H&N, and OSCAR (Friedlingstein et al., 2020). Gross emissions 1990-2019 for BLUE, H&N, OSCAR are 17, 9.6 and 19 GtCO$_2$ yr$^{-1}$
1 respectively. For 1990-2019 maximum average differences are 9.1 and 7.8 GtCO₂ yr⁻¹ for gross emissions and removals, respectively (Friedlingstein et al., 2020). Note that 2016-2019 is extrapolated in H&N and 2019 in OSCAR based on the anomalies of the net flux for the gross fluxes. Differences in the models underlying this observed variability are reported in Table 4. In the longer term, a consistent general upward trend since 1850 across models is reversed during the second part of the 20th century. Since the 1980s, however, differing trends across models are related to, among other things, different land-use forcings (Gasser et al., 2020). Further differences between BLUE and H&N can be traced in particular to: (1) differences in carbon densities between natural and managed vegetation, or between primary and secondary vegetation; (2) a higher allocation of cleared and harvested material to fast turnover pools in BLUE compared to H&N; and (3) to the inclusion sub-grid scale transitions (Bastos et al., 2021).

Uncertainties in CO₂-LULUCF emissions can be more comprehensively assessed through comparisons across a suite of dynamic global vegetation models (DGVM) (Friedlingstein et al., 2020). DGVM models are not combined in the CO₂-LULUCF mean estimate in our data because the typical DGVM setup includes the loss of additional sink capacity, which makes up about 40% of the DGVM estimate in recent years (Obermeier et al., 2020) and is excluded in bookkeeping estimates. Nonetheless, a CO₂-LULUCF estimate from the DGVM multi-model mean remains consistent with the average estimate from the bookkeeping models, as shown in Figure 1. Variation across DGVMs is large with a standard deviation at around 1.8 GtCO₂ yr⁻¹, but is still smaller than the average difference between bookkeeping models at 2.6 GtCO₂ yr⁻¹ as well as the current estimate of H&N (Houghton and Nassikas, 2017) and its previous model versions (Houghton et al., 2012). DGVMs differ in methodology, input data and how comprehensively they represent land-use-related processes. In particular land management, such as crop harvesting, tillage, or grazing (all implicitly included in observation-based carbon densities of bookkeeping models) can alter CO₂ flux estimates substantially, but are included to varying extents in DGVMs, thus increasing model spread (Arneth et al., 2017). For all types of models, land-use forcing is a major determinant of emissions and removals, and its high uncertainty impacts CO₂-LULUCF estimates (Hartung et al., 2021). The reconstruction of land-use change of the historical past, which has to cover decades to centuries of legacy LULUCF fluxes, is based on sparse data or proxies (Hurtt et al., 2020; Klein Goldewijk et al., 2017), while satellite-based products suffer from complications in distinguishing natural from anthropogenic drivers (Hansen et al., 2013; Li et al., 2018) or accounting for small-scale disturbances and degradation (Matricardi et al., 2020). Lastly, regional carbon budgets can be substantially over- or underestimated when carbon embodied in trade products is not accounted for (Ciais et al., 2021).

We base our uncertainty assessment on Friedlingstein et al. (2020) and take ±2.6 GtCO₂ yr⁻¹ as a best-value judgement for the ±1σ uncertainty range (thus ±5.1 GtCO₂ yr⁻¹ for ±2σ) in CO₂-LULUCF emissions, constant over the last decades. This absolute uncertainty estimate presented above corresponds roughly to a relative uncertainty of about ±50% over 1970-2019, which is much higher than for most fossil-emission terms, but reflects the large model spread and large differences between the current estimate of H&N and its previous model version (Houghton et al., 2012). This corresponds to a relative uncertainty of about
±80% for a 90% confidence interval (5th-95th percentile) and is larger but still broadly in line with the upper end of the relative uncertainty of ±50 - ±75% considered in AR5 (Blanco G. et al., 2014). Much larger uncertainties in CO₂-LULUCF emissions have been identified across the literature, but were traced back to different definitions used in various modelling frameworks (Pongratz et al., 2014) as well as inventory data (Grassi et al., 2018). Overall, we use a relative uncertainty estimate of about ±70% for a 90% confidence interval. This recognizes the choice of a constant absolute uncertainty estimate taken elsewhere (Friedlingstein et al., 2020) and in recognition of a possible trend towards higher CO₂-LULUCF emissions estimates in more recent years.

Finally, note that attempts to constrain the estimates of CO₂-LULUCF emissions by observed biomass densities have been undertaken, but were successful only in some non-tropical regions (Li et al., 2017). While providing valuable independent and observation-driven information, remote-sensing derived estimates have limited applicability for model evaluation for the total CO₂-LULUCF flux, since they usually only quantify vegetation biomass changes and exclude legacy emissions from the pre-satellite era. Further, with the exception of the (pan-tropical) estimates by Baccini et al. (2012) they either track committed instead of actual emissions (e.g. Tyukavina et al., 2015), combine a static carbon density map with forest cover changes, or include the natural land sink (e.g. Baccini et al., 2017) to infer fluxes directly from the carbon stock time series – none of which fully distinguishes natural from anthropogenic disturbances.

Table 4 - Key differences between global bookkeeping estimates for CO₂-LULUCF emissions. Notes: DGVM – dynamic global vegetation model; LUH2 and FAO refer to land-use forcing datasets; arrows indicate tendency of process to increase or decrease emissions compared to the other estimates’ choice.

| Geographical computation | BLUE<sup>a</sup> | H&N<sup>b</sup> | OSCAR<sup>c</sup> |
|-------------------------|----------------|---------------|-----------------|
| scale of computation    | 0.25 degree gridscale | country | 10 regions and 5 biomes |
| Carbon densities of soil and vegetation | literature-based | based on country reporting | calibrated to DGVMs |
| Land-use forcing | LUH2<sup>d,e</sup> | FAO<sup>f</sup> | LUH2 and FAO<sup>d,e,f</sup> |

Representation of processes (indicative effect on AFOLU CO₂ emissions)

| Sub-grid scale (”gross”) land-use transitions | yes (†) | no (↓) | yes (†) |
| Pasture conversion | From all natural vegetation types proportionally (†) | from grasslands first (↓) | from all natural vegetation types proportionally (†) |
### 3.3 Anthropogenic CH₄ emissions

About 60% of total global methane emissions come from anthropogenic sources (Saunois et al., 2020). These are linked to a range of different sectors: agriculture, fossil production and use, waste as well as biomass and biofuel burning. Methane emissions can be derived either using bottom-up (BU) estimates that rely on anthropogenic inventories such as EDGAR (Janssens-Maenhout et al., 2019), land surface models that infer part of natural emissions (Wania et al., 2013) or observation-based upscaling for some specific sources such as geological sources (e.g. Etiope et al., 2019). Alternatively, top-down (TD) approaches can be used, such as atmospheric transport models that assimilate methane atmospheric observations to estimate past methane emissions (Houweling et al., 2017). Some TD systems aim to optimize certain emission sectors based on differences in their spatial and temporal distributions (e.g. Bergamaschi et al., 2013), while other only solve for net emissions at the surface. Then the partitioning of TD posterior (output) fluxes between specific source sectors (e.g. Fossil vs. BB&F) is carried out with various degrees of uncertainty depending of the methods and the degree of refinement of sectors, but often rely on ratios from the prior knowledge of fluxes. Comprehensive assessments of methane sources and sinks have been provided by Saunois et al. (2016, 2020) and Kirschke et al. (Kirschke et al., 2013).

EDGAR (Crippa et al., 2019; Janssens-Maenhout et al., 2019) is one of multiple global methane BU inventories available. Other inventories – namely GAINS (Höglund-Isaksson, 2012), US-EPA (EPA, 2011, 2021), CEDS (Hoesly et al., 2018; McDuffie et al., 2020; O’Rourke et al., 2020) as well as FAOSTAT-CH₄ (Federici et al., 2015; Tubiello, 2018; Tubiello et al., 2013) – can differ in terms of their country and sector coverage as well as detail. EDGAR, CEDS, US-EPA and GAINS cover all major source sectors (fossil fuels, agriculture and waste, biofuel) – except large scale biomass burning – but this can be added from different databases such as FINN (Wiedinmyer et al., 2011), GFAS (Kaiser et al., 2012), GFED (Giglio et al., 2013) or QFED (Darmenov and da Silva, 2013). Much like CO₂ FFI, these inventories of anthropogenic emissions are not completely independent as they either follow the same IPCC methodology to derive emissions, rely on similar data sources (e.g., FAOSTAT activity data for agriculture, reported fossil fuel production), or draw on reported country inventory data. However, they may differ in the assumptions and data used for the calculation. While the US-EPA inventory uses the reported emissions by the countries to UNFCCC, other inventories produce their own estimates using a consistent approach for all countries, and country specific activity data, emission factor and technological abatement when available. FAOSTAT and

| Distinction rangeland vs pasture | yes (↓) | no (↑) | no (↑) |
|---------------------------------|---------|--------|--------|
| Coverage peat drainage (as in Global Carbon Budget 2020) | World (↑) | South East Asia (↓) | World (↑) |

Literature: ^{a} (Hansis et al., 2015); ^{b} (Houghton and Nassikas, 2017); ^{c} (Gasser et al., 2020); ^{d} (Hurtt et al., 2020); ^{e} (Chini et al., 2020); ^{f} (Nations, 2015); ^{g} (Conchedda and Tubiello, 2020); ^{h} (Hooijer et al., 2010)
EDGAR mostly apply a Tier 1 approach to estimate methane emissions while GAINS uses a Tier 2 approach (Högland-Isaksson et al., 2020). CEDS is based on pre-existing emission estimates from FAOSTAT and EDGAR and then scales these emissions to match country-specific inventories, largely those reported to UNFCCC.

Global anthropogenic CH$_4$ emission estimates are compared in Figure 1. EDGARv5 has revised total global CH$_4$ emissions about 10 Mt CH$_4$ yr$^{-1}$ higher than EDGARv4.3.2 due to a higher estimate for the waste sector (see supplementary material). Subsequent revisions of the estimation methodology in EDGARv6 in alignment with the IPCC guidelines refinement (IPCC, 2019) lead to very substantial differences in total CH$_4$ emissions of up to 50 MtCH$_4$yr$^{-1}$ before the 1990s, but these differences are smaller ranging from 1-13 MtCH$_4$yr$^{-1}$ since the 2000s. The cause of these differences is a new procedure to separately estimate of the venting component for gas and oil, in the venting and flaring sector (1B2a/b2). Differences across different versions of the EDGAR dataset are shown in the Supplementary Material (Fig. SM-1). US-EPA show the lowest estimates probably due to missing estimates from a significant number of countries not reporting to UNFCCC (US-EPA2020 includes estimates from only 195 countries) and incomplete sectoral coverage. EDGARv6 estimates of anthropogenic CH$_4$ emissions, as used here, are in the upper range of the different inventories across most anthropogenic sources. However, they do not cover CH$_4$ emissions from forest and grassland burning, which amount about 10-12 Mt per year.

Saunois et al (2020) provide estimates of methane sources and sinks based on BU and TD approaches associated with an uncertainty range based on the minimum and maximum values of available studies (because for many individual source and sink estimates the number of studies is often relatively small). Thus, they do not consider the uncertainty of the individual estimates. As shown in Table 5, uncertainties in total global methane emissions across all anthropogenic and natural sources are comparatively small at ±6% - a range larger than errors in transport models only (Locatelli et al., 2015). However, uncertainty in the chemical sink was not fully considered in the TD estimates in Saunois et al (2020). Uncertainty on the global burden of OH is about 10-15%, which translates to an uncertainty of approximately ±9% on total global emissions (Zhao et al., 2020). Based on both TD and BU ensemble, uncertainty (reported as the minimum- maximum range across estimates) on the global anthropogenic methane emissions is about ±10% to ±30% depending on the category, with larger uncertainty in the fossil fuel sectors than in the agriculture and waste sector (Saunois et al., 2020). However, these uncertainties are underestimated as they do not consider the uncertainty in each individual estimate, which includes potential uncertainties in activity data, emission factors, and equations used to estimate emissions.

Uncertainties in EDGARv5 CH$_4$ emissions using a Tier 1 approach are estimated at -33% to +46% at 2σ, but there is great variability across individual sectors ranging from ±30% (agriculture) to more than ±100% (fuel combustion), with high uncertainties in oil and gas sector (±93%) and coal fugitive emissions (±65%) (Solazzo et al., 2021). Inventories at national scale, such as in the USA also show large uncertainties depending on the sector (NASEM, 2018), though the activity data uncertainty may be lower than those for less developed countries. For example, global inventories, such as EDGAR, estimate
uncertainties in national anthropogenic emissions of about ± 32% for the 24 member countries of OECD, and up to ±57% for other countries, whose activity data are more uncertain (Janssens-Maenhout et al., 2019).

Table 5 - Uncertainties estimated for methane sources at the global scale: based on ensembles of bottom-up (BU) and top-down (TD) estimates, national reports and specific uncertainty assessments of EDGAR

| Source of Emissions | Estimated uncertainty in USA inventories | Estimated uncertainty in EDGAR | Estimated uncertainty in EDGAR | Global inventories uncertainty range | Saunois et al. (2020) BU uncertainty range | Saunois et al. (2020) TD uncertainty range |
|---------------------|-----------------------------------------|-------------------------------|-------------------------------|------------------------------------|---------------------------------|---------------------------------|
| Total global anthropogenic sources (incl. Biomass burning) | ±47% | -33% to +46% | ±8% | ±6% | ±6% |
| Total global anthropogenic sources (excl. Biomass burning) | ±47% | -33% to +46% | ±8% | ±6% | ±6% |
| Agriculture and Waste | | | | | | |
| Rice | na | | | 31-38% | ±22% | ±20% |
| | | | | | | ±60% |
| Enteric fermentation and manure management | ±10 to 20% | | | ±5% | ±8% | - |
| | ±20% and up to ±65% | | | | | |
| Landfills and Waste | ±10% but likely much larger | | | 78-79% | ±17% | ±7% |
| Fossil fuel production & use | | | | | ±20% | ±25% |
| Coal | -15% to +20% | -75% | 65% | 60-74% | ±40% | ±28% |
| Oil and gas | -20% to +150% | 93% | ±19% | ±15% | - | - |
| Other | na | ±100% | ±100% | ±64% | ±130%* | - |
| Biomass and biofuel burning | | | | | | |
| Biomass burning | | | | | ±25% | ±25% |
| | | | | ±35% | | |
Biofuel burning Included in “Other” 147% +/-24% ±17% -

a Based on (NASEM, 2018)
b Uncertainty calculated as ((min-max)/2)/mean*100 from the estimates of year 2017 of the six inventories plotted in Figure 1. This does not consider uncertainty on each individual estimate.
c Uncertainty calculated as ((min-max)/2)/mean*100 from individual estimates for the 2008-2017 decade. This does not consider uncertainty on each individual estimate, which is probably larger than the range presented here.
d Based on EDGARv432 for year 2010 (Janssens-Maenhout et al., 2019).
e Based on Solazzo et al. (2021)
f Mainly due to difficulties in attributing emissions to small specific emission sector.

The most recent UN emissions gap report (UNEP, 2020) gives an uncertainty range for global anthropogenic methane emissions with one standard deviation of ±30% (i.e. ±60% for 2σ), which is slightly higher than recent estimates in the literature. On the other hand, IPCC AR5 provides a comparatively low estimates at ±20% for a 90% confidence interval. Overall, we apply a best value judgment of ±30% for global anthropogenic methane emissions for a 90% confidence interval. This is justified by the large uncertainties reported in the methane budgets (Kirschke et al., 2013; Saunois et al., 2016, 2020) as well as for FAO activity statistics by Tubiello et al. (Tubiello et al., 2015), is broadly in line with the uncertainties quantified for EDGARv5.

### 3.4 Anthropogenic N₂O emissions

Anthropogenic N₂O emissions occur in a number of sectors, namely agriculture, fossil fuel and industry, biomass burning, and waste. The agriculture sector consists of four components: direct and indirect emissions from soil and water bodies (inland, coastal, and oceanic waters), manure left on pasture, manure management, and aquaculture. Besides these main sectors, a final ‘other’ category represents the sum of the effects of climate, elevated atmospheric CO₂, and land cover change. This is a new sector that was developed as part of the global nitrous oxide budget (Tian et al., 2020) – a recent assessment to quantify all sources and sinks of N₂O emissions, updating previous work (Kroeze et al., 1999; Mosier et al., 1998; Mosier and Kroeze, 2000; Syakila and Kroeze, 2011). Overall, anthropogenic sources contributed just over 40% to total global N₂O emissions (Tian et al., 2020).

There are a variety of approaches for estimating N₂O emissions. These include inventories (Janssens-Maenhout et al., 2019; Tian et al., 2018; Tubiello et al., 2013), statistical extrapolations of flux measurements (Wang et al., 2020), and process-based land and ocean modelling (Tian et al., 2019; Yang et al., 2020). There are at least five relevant global N₂O emissions inventories available: EDGAR (Crippa et al., 2019, 2021; Janssens-Maenhout et al., 2019), GAINS (Höglund-Isaksson, 2012), FAO-N₂O (Tubiello, 2018; Tubiello et al., 2013), CEDS (Hoesly et al., 2018; McDuffie et al., 2020; O’Rourke et al., 2020) and GFED (Giglio et al., 2013). While EDGAR and GAINS cover all sectors except biomass burning, FAOSTAT-N₂O is
focused on agriculture and biomass burning and GFED on biomass burning only. As shown in Figure 1 EDGAR, GAINS, CEDS and FAOSTAT emissions are consistent in magnitude and trend. Recent revisions in estimating indirect N\textsubscript{2}O emissions in EDGARv6 lead to an average increase of 1.5% yr\textsuperscript{-1} in total N\textsubscript{2}O emissions estimates between 1999 and 2018 compared to EDGARv5 (differences before 1999 were negligible at less than 1% yr\textsuperscript{-1}). Differences across different versions of the EDGAR dataset are shown in the Supplementary Material (Fig. SM-1). The main discrepancies across different global inventories are in agriculture, where emission estimates from the global nitrous oxide budget (also referred to as “GCP”) (Tian et al., 2020) and FAOSTAT are on average 1.5 Mt N\textsubscript{2}O yr\textsuperscript{-1} higher than those from GAINS and EDGAR during 1990-2016, due to much higher estimates of direct emissions from fertilised soils and manure left on pasture. GCP provides the largest estimate, because it synthesised from the other three inventories and further informed by additional bottom-up modelling estimates – and is as such more comprehensive in scope (Figure 1). In particular, it includes an additional sector that considers the sum of the effects of climate, elevated atmospheric CO\textsubscript{2}, and land cover change (Tian et al., 2020). EDGAR estimates of anthropogenic N\textsubscript{2}O emissions as used in this dataset should therefore be considered as lower bound estimates.

Anthropogenic N\textsubscript{2}O emissions estimates are subject to considerable uncertainty – larger than those from FFI-CO\textsubscript{2} or CH\textsubscript{4} emissions. N\textsubscript{2}O inventories suffer from high uncertainty on input data, including fertiliser use, livestock manure availability, storage and applications (Galloway et al., 2010; Steinfeld et al., 2010) as well as nutrient, crops and soils management (Ciais et al., 2014; Shcherbak et al., 2014). Emission factors are also uncertain (Crutzen et al., 2008; Hu et al., 2012; IPCC, 2019; Yuan et al., 2019) and there remains several sources that are not yet well understood (e.g. peatland degradation, permafrost) (Elberling et al., 2010; Wagner-Riddle et al., 2017; Winiwarter et al., 2018). Model-based estimates face uncertainties associated with the specific model configuration as well as parametrisation (Buitenhuis et al., 2018; Tian et al., 2019, 2020). Total uncertainty is also large because N\textsubscript{2}O emissions are dominated by emissions from soils, where our level of process understanding is rapidly changing.

For EDGARv4.3.2 uncertainties in N\textsubscript{2}O emissions are estimated based on default values (IPCC, 2006) at ±42% for 24 OECD90 countries and at ±93% for other countries for a 95% confidence interval (Janssens-Maenhout et al., 2019). However, Solazzo et al. (2021) arrive at substantially larger values for EDGARv5 allowing for correlation of uncertainties between sectors, countries and regions. At a sector level, uncertainties are larger for agriculture than for biomass burning, fossil fuel and industry, and waste. In the recent Emissions Gap Report (UNEP, 2020) relative uncertainties for global anthropogenic N\textsubscript{2}O emissions are estimated at ±50% for a 68% (1\sigma) confidence interval. This is larger than the ±60% uncertainties reported in IPCC AR5 for a 90% confidence interval (Blanco G. et al., 2014), but is comparable with the ranges for anthropogenic emissions in the global N\textsubscript{2}O budget (Tian et al., 2020). Overall, we assess the relative uncertainty for global anthropogenic N\textsubscript{2}O emissions at ±60% for a 90% confidence interval.
Table 6 - Comparison of four global N₂O inventories: EDGAR (Crippa et al. 2019a; Janssens-Maenhout et al. 2019); GCP (Tian et al. 2020); GAINS (Höglund-Isaksson 2012); FAOSTAT (Tubiello 2018; Tubiello et al. 2013)

| Name      | Time coverage | Geographical coverage | Activity split | IPCC emissions factors | Reported emissions in 2015 (in MtN₂O) |
|-----------|---------------|-----------------------|----------------|------------------------|--------------------------------------|
| EDGAR     | 1970-2018     | Global, countries     | 4 main sectors, 24 sub-sectors | Yes | 6 | 2.4 | 0.05 | 0.4 | - | 8.9 |
| GCP       | 1980-2016     | Global, regions       | 5 main sectors, 14 sub-sectors | no | 8.4 | 1.6 | 1.1 | 0.6 | 0.3 | 11.9 |
| GAINS     | 1990-2015 (every 5 years) | Global, regions | 3 main sectors, 16 sub-sectors | no | 6.8 | 1.3 | - | 0.7 | - | 8.8 |
| FAOSTAT   | 1961-2017     | Global, countries     | 2 main sectors, 9 sub-sectors | Yes | 8.3 | - | 0.9 | - | - | 9.2 |

3.5 Fluorinated gases

Fluorinated gases comprise over a dozen different species that are released mainly in the industry sector for use as refrigerants, solvents and aerosols. Here we compare global emissions of F-gases estimated in EDGARv5 to top-down values from the 2018 World Meteorological Organisation’s (WMO) Scientific Assessment of Ozone Depletion (Engel and Rigby, 2018; Montzka and Velders, 2018). The top-down estimates were based on measurements by the Advanced Global Atmospheric Gases Experiment (AGAGE, Prinn et al., 2018) and National Oceanic and Atmospheric Administration (NOAA, Montzka et al., 2015), assimilated into a global box model (using the method described in Engel and Rigby, et al., 2018 and Rigby et al., 2014)). Uncertainties in the top-down estimates are due to measurement and transport model uncertainty, but as F-gas emissions are entirely anthropogenic in nature they are much better known than CO₂, CH₄, N₂O, where there are also large natural fluxes. For substances with relatively short lifetimes (~50 years or less), uncertainties are typically dominated by uncertainties in the atmospheric lifetimes. Comparisons between the EDGARv5 and WMO 2018 estimates were available for HFCs 125, 134a, 143a, 152a, 227ea, 23, 236fa, 245fa, 32, 365mfc and 43-10-mee, PFCs CF₄, C₂F₆, C₃F₈ and c-C₄F₁₀, and SF₆. For the higher molecular weight PFCs (C₅F₁₁, C₆F₁₃, C₇F₁₄, C₈F₁₆), top-down estimates were not available in WMO (2018). Top-down estimates have previously been published for these compounds (e.g. Ivy et al., 2012), however, this comparison is
not included here due to their very low emissions. For a small number of species, global top-down estimates are available for some years, based on an independent atmospheric model to that used in WMO (2018), although most of these inversions use similar measurement datasets; Fortems-Cheiney, et al. (2015) for HFC-134a, Lunt, et al. (2015) for HFC-134a, -125, -152a, -143a and -32 and Rigby, et al (2010) for SF6.

Figure 2 - Comparison of top-down and bottom-up estimates for individual species in EDGARv5. C₄F₈, C₅F₁₂, C₆F₁₄ and C₇F₁₆ are excluded. Top-down estimates from WMO 2018 (Engel and Rigby, 2018; Montzka and Velders, 2018) are shown as blue lines with blue
shading indicating 1-sigma uncertainties. Bottom-up estimates from EDGARv5 are shown in red dotted lines. Top-down estimates for some species are shown from Rigby, et al. (2010), Lunt, et al. (2015) and Fortems-Cheiney, et al. (2015).

Figure 3 – Comparison between top-down estimates and bottom-up EDGARv5 inventory data on GHG emissions. Left panel: Total GWP100-weighted emissions of F-gases in EDGARv5 (red dashed line, excluding C4F10, C5F12, C6F14 and C7F16) compared to top-down estimates based on AGAGE and NOAA data from WMO (2018) (blue lines; Engel and Rigby, (2018); Montzka and Velders (2018)). Right panel: Top-down aggregated emissions for the three most abundant CFCs (-11, -12 and -113) and HCFCs (-22, -141b, -142b) not covered in bottom-up emissions inventories are shown in green and orange, with the area between the two respective lines representing 1-sigma uncertainties.

The comparison of global top-down and bottom-up emissions for each EDGARv5 F-gas species (excluding heavy PFCs) is shown in Figure 2 for the years 1980 – 2016 (or a subset thereof, depending on the availability of the top-down estimates). Where available, the various top-down estimates agree with each other within uncertainties. The magnitude of the difference between WMO (2018) and EDGARv5 estimates varies markedly between species; for CF4, the median annual ratio between the top-down and bottom-up estimates is close to 1.0, whereas for c-C4F8 it is more than 100. Such differences have been previously noted, for example, by Mühle, et al. (2019) as well as in some earlier papers. For SF6, the relatively close agreement between a previous version of EDGAR (v4) and a top-down estimate has been discussed in Rigby, et al. (2010). They estimated uncertainties in EDGARv4 of ±10% to ±15%, depending on the year, and indeed, top-down values were consistent within these uncertainties. For CF4, these is close agreement between EDGARv4 and atmospheric observations after 1991, while for C2F6 there is closer agreement before 1991 (Mühle et al., 2010). This remains the case here for EDGARv5. However, it should...
be noted that some assumptions within EDGAR had previously been validated against atmospheric observations, hence EDGARv4 might be considered a hybrid of top-down and bottom-up methodologies for these species, as some parameters may have been chosen based on comparison with atmospheric observations. Mühle, et al. (2010) noted a substantial gap between EDGARv4 and top-down estimates (with EDGARv4 emissions being less than 30% of the top-down values before 2008), which has apparently closed considerably in recent years in EDGARv5. However, for this species, as for many others, the cause of this discrepancy is not known.

When species are aggregated into an F-gas total, weighted by their 100-year GWPs (Figure 3), the EDGARv5 estimates are around 10% lower than the WMO 2018 values in the 1980s. Subsequently, EDGARv5 estimates grow more rapidly than the top-down values and are almost 30% higher than WMO 2018 by the 2010s. Given that detailed uncertainty estimates are not available for all EDGAR F-gas species, we base our uncertainty estimate solely on this single comparison with the top-down values, and therefore suggest an uncertainty in aggregated F-gas emissions of ±30% for a 90% confidence interval. For individual species, the magnitude of this discrepancy can be orders of magnitude larger.

The F-gases in EDGARv5 do not include chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and some perfluorinated species such as NF$_3$ – most of these species being regulated under the Montreal Protocol. Historically, total CO$_2$-equivalent F-gas emissions have been dominated by the CFCs (Engel and Rigby, 2018). In particular, during the 1980s, peak annual emissions due to CFCs reached 9.1±0.4 GtCO$_2$eqyr$^{-1}$ (Figure 3), comparable to that of CH$_4$, and substantially larger than the 2019 emissions of the gases included in EDGARv5 (1.6 GtCO$_2$eq) (Table 7). Subsequently, following the controls of the Montreal Protocol, emissions of CFCs declined substantially, while those of HCFCs and HFCs rose, such that CO$_2$eq emissions of the HFCs, HCFCs and CFCs were approximately equal by 2016, with a smaller contribution from PFCs, SF$_6$ and some more minor F-gases. Therefore, the GWP-weighted F-gas emissions in EDGARv5, which are dominated by the HFCs, represent less than half of the overall CO$_2$eq F-gas emissions in 2018.

3.6 Aggregated GHG emissions

Based on our assessment of relevant uncertainties above, we apply constant, relative uncertainty estimates for GHGs at a 90% confidence interval that range from relatively low for CO$_2$ FFI (±8%), to intermediate values for CH$_4$ and F-gases (±30%), to higher values for N$_2$O (±60%) and CO$_2$ from LULUCF (±70%). To aggregate these and estimate uncertainties for total greenhouse gases in terms of CO$_2$-eq emissions, we taking the square root of the squared sums of absolute uncertainties for individual (groups of) gases, using 100-year Global Warming Potentials (GWP100) to weight emissions of non-CO$_2$ gases but excluding uncertainties in the metric itself (see Section 3.7). Overall, this is broadly in line with IPCC AR5 (Blanco G. et al., 2014), but provides important adjustments both in the evaluation of uncertainties (CH$_4$, F-gases, CO$_2$-LULUCF) as well as the approach in reporting total uncertainties across greenhouse gases.
3.7 GHG emission metrics

GHG emission metrics are necessary if emissions of non-CO₂ gases and CO₂ are to be aggregated into CO₂eq emissions. GWP-100 is the most common metric and has been adopted under the transparency framework for the Paris Agreement (UNFCCC, 2019), but many alternative metrics exist in the scientific literature. The most appropriate choice of metric depends on the climate policy objective and the specific use of the metric to support that objective (i.e. why do we want to aggregate or compare emissions of different gases? What specific actions do we wish to inform?)

Different metric choices and time horizons can result in very different weightings of the emissions of Short-lived Climate Forcers (SLCF), such as methane. For example, 1t CH₄ represents as much as 86t CO₂eq if a Global Warming Potential is used with a time horizon of 20 years and including climate-carbon cycle feedbacks, or as little as 4t CO₂eq if the Global Temperature change Potential (GTP) is used with a time horizon of 100 years and excluding climate-carbon cycle feedbacks (Myhre et al., 2013). More recent metric developments that compare emissions in new ways – e.g. the additional warming from sustained changes in SLCF emissions compared to pulse emissions of CO₂ – increase the range of metric values further and can even result in negative values, if SLCF emissions are falling rapidly (Allen et al., 2018; Cain et al., 2019; Collins et al., 2019; Lynch et al., 2020).

The contribution of SLCF emissions to total GHG emissions expressed in CO₂eq thus depends critically on the choice of GHG metric and its time horizon. However, even for a given choice, the metric value for each gas is also subject to uncertainties. For example, the GWP-100 for methane has changed from 21 based on the IPCC Second Assessment Report in 1995 to 28 or 34 based on the IPCC AR5 (including feedbacks). These changes and remaining uncertainties arise from parametric uncertainties, differences in methodological choices, and changes in metric values over time, due to changing background conditions.

- Parametric uncertainties arise from uncertainties in climate sensitivity, radiative efficacy and atmospheric lifetimes of CO₂ and non-CO₂ gases, etc. The IPCC AR5 assessed the parametric uncertainty of GWP for methane as ±30% and ±40% for time horizons of 20 and 100 years, and ±20% and ±30% for gases with atmospheric lifetimes of a century or more. The uncertainty of GTP-100 for methane was estimated at ±75% (Myhre et al., 2013), which is larger than the uncertainty in a forcing-based metric due to due to uncertainties in climate responses to forcing (e.g., climate sensitivity). Further changes in metric values for methane and other gases within this uncertainty range are likely, given recent re-evaluations of the direct forcing of methane (Etminan et al., 2016) and adjustment of effective radiative forcing (Smith et al., 2020).

- Methodological choices introduce a different type of uncertainty, namely which indirect effects are included in the calculation of metric values and the strength of those feedbacks. For methane, indirect forcing caused by
photochemical decay products (mainly tropospheric ozone and stratospheric water vapour) contributes almost 40% of the total forcing from methane emissions. More than half of the changes in GWP-100 values for methane in successive IPCC assessments from 1995 to 2013 are due to re-evaluations of these indirect forcings. These uncertainties are incorporated in the above uncertainty estimates. In addition, warming due to the emission of non-CO$_2$ gases extends the lifetime of CO$_2$ already in the atmosphere through climate-carbon cycle feedbacks (Friedlingstein et al., 2013). Including these feedbacks results in higher metric values for all non-CO$_2$ gases, but the magnitude of this effect is uncertain; e.g. the IPCC AR5 found the GWP-100 value for methane without climate-carbon cycle feedbacks to be 28, whereas including this feedback would raise the value to between 31 and 34 (Gasser et al., 2016; Myhre et al., 2013; Sterner and Johansson, 2017).

- A third uncertainty arises from changes in metric values over time. Metric values depend on the radiative efficacy of CO$_2$ and non-CO$_2$ emissions, which in turn depend on the changing atmospheric background concentrations of those gases. Rising temperature can further affect the lifetime of some gases and hence their contribution to forcing over time (Reisinger et al., 2011). Successive IPCC assessments take changing starting-year background conditions into account, which explains part of the changes in GWP-100 metric values in different reports. Current IPCC convention calls for metrics to be calculated using constant background concentrations. Using time-changing background concentrations for the future, i.e. using a specific future concentration scenario, will result in additional changes in metric values. Applying a single metric value to a time series of emissions is therefore only an approximation of the correct metric value for any given emissions year, as e.g. the correct GWP-100 value for methane emitted in the year 1970 will be different to the GWP-100 value for an emission in the year 2018. However, the literature does not offer a complete set of GWP-100 metric values for past concentrations and climate conditions.

Overall, we estimate the uncertainty in GWP-100 metric values, especially if applied to extended emission time series, as ±50% for methane and other SLCFs, and ±40% for non-CO$_2$ gases with longer atmospheric lifetimes (specifically, those with lifetimes longer than 20 years). If uncertainties in GHG metrics are considered, the overall uncertainty of total GHG emissions in 2018 increases from ±11% to ±24%. (However, in the following sections we do not include GWP uncertainties in our global, regional or sectoral estimates).

For the purpose of this paper, we use GWP-100 metric values from the IPCC AR5 (Myhre et al., 2013) without climate-carbon cycle feedbacks. Even though climate-carbon cycle feedbacks are considered a robust feature of the climate system, the issue was only emerging during the IPCC AR5 and the methodology used to include this in metric calculations was indicative only. Subsequent studies (Gasser et al., 2016; Sterner and Johansson, 2017) suggest that revisions to the simple estimation method in IPCC AR5 are necessary.
As mentioned above, the most appropriate metric to aggregate GHG emissions depends on the objective. One such objective can be to understand the contribution of emissions in any given year to warming, while another can be to understand the contribution of cumulative emissions over an extended time period to warming. Sustained emissions of SLCFs such as methane do not cause the same temperature response as sustained emissions of CO$_2$. Showing superimposed emission trends of different gases over multiple decades using GWP-100 as equivalence metric therefore does not necessarily represent the overall contribution to warming from each gas over that period. In Figure 4 we therefore also show the modelled warming from emissions of each gas or group of gases - calculated using the reduced-complexity climate model FAIRv1.6 and calibrated to reproduce the pulse-response functions for each gas consistent with the IPCC AR5 (Myhre et al., 2013). Despite some differences compared to the contribution of each gas, based on GHG emissions expressed in CO$_2$eq using GWP-100 (see Fig. 3), Figure 4 highlights that GWP-100 does not provide a vastly different story than modelled warming with CO$_2$ being the dominant and CH$_4$ being the second most important contributor to GHG-induced warming. Other metrics such as GWP* (Cain et al., 2019) offer an even closer resemblance between cumulative CO$_2$eq emissions and temperature change if that is the key objective, especially if emissions are no longer rising but potentially falling, as in mitigation scenarios.
Figure 4 - Contribution of different greenhouse gases to global warming over the period 1750 to 2018. Top row: contributions from estimated with the FAIR reduced-complexity climate model. Major GHGs and aggregates of minor gases as a timeseries in a) and as a total warming bar chart with 5 % to 95 % uncertainty range added in b). Bottom row: contribution from short-lived climate forcers as a timeseries in c) and as a total warming bar chart with 5 % to 95 % uncertainty range added in d). The dotted line in c) gives the net temperature change from short-lived climate forcers. F-Kyoto/Paris includes the gases covered by the Kyoto Protocol and Paris Agreement, while F-other includes the gases covered by the Montreal Protocol.

4 Results

Here we analyse global trends in anthropogenic GHG emissions in three time periods: (1) 1970-2019 to characterise the main trends in the data; (2) 2010-2019 to focus on the last decade and developments since IPCC AR5, which had its data cut-off for the year 2010 (Blanco G. et al., 2014); and (3) 2019 emission levels.
4.1 Global anthropogenic greenhouse gas emissions for 1970-2019

There is high confidence that global greenhouse gas emissions have increased every decade from an average of 32±4.3 GtCO₂eq yr⁻¹ for the decade of the 1970s to an average of 56±6.0 GtCO₂eq yr⁻¹ during 2010-2019 as shown in Table 7. The decadal growth rate initially decreased from 1.7% yr⁻¹ in the 1970s (1970-1979) to 0.9% yr⁻¹ in the 1990s (1990-1999). After a period of accelerated growth during the 2000s (2000-2009) at 2.4% yr⁻¹, triggered mainly by growth in CO₂-FFI emissions from rapid industrialisation in China (Chang and Lahr, 2016; Minx et al., 2011), relative growth has decreased again to 1.1% yr⁻¹ during the most recent decade (2010-2019). Uncertainties in aggregate GHG emissions have decreased over time as the share of less uncertain CO₂-FFI emission estimates increased and the share of more uncertain emission estimates such as CO₂-LULUCF or N₂O decreased.

Table 7 – Average annual anthropogenic GHG emissions and emissions growth by decade and (groups of) gases for 1970-2019: CO₂ from fossil fuel combustion and industrial processes (FFI); CO₂ from land use, land-use change and forestry (LULUCF); methane (CH₄); nitrous oxide (N₂O); fluorinated gases (F-gases). Aggregate GHG emission trends by groups of gases reported in GtCO₂eq converted based on global warming potentials with a 100-year time horizon (GWP-100) from the IPCC Fifth Assessment Report (Myhre et al., 2013). Uncertainties are reported for a 90% confidence interval (see Section 3). Levels and growth are average values over the indicated time period. Additional supplementary tables show similar average annual GHG emissions by decade also for major sectors (Table SM-2) and regions (Table SM-2).

| Decade       | CO₂ FFI | CO₂ LULUCF | CH₄    | N₂O    | Fluorinated gases | GHG    |
|--------------|---------|------------|--------|--------|-------------------|--------|
|              | Levels  | Growth     | Levels | Growth | Levels            | Growth |
| 2010-2019    | 36±2.9  | 1.0%       | 5.7±0.1| 1.8%   | 10±3.1           | 0.9%   |
| 2000-2009    | 29±2.3  | 3.0%       | 5.3±3.7| 0.4%   | 9.2±2.8          | 1.6%   |
| 1990-1999    | 24±1.9  | 1.2%       | 5.0±3.5| -0.1%  | 8.5±2.5          | 0.3%   |
| 1980-1989    | 21±1.6  | 1.6%       | 4.7±3.3| 1.8%   | 7.9±2.4          | 1.0%   |
| 1970-1979    | 18±1.4  | 2.8%       | 4.6±3.2| -1.6%  | 7.4±2.2          | 1.2%   |
| 1970         | 16±1.3  | 5.0±3.5    | 6.9±2.1| 1.5±0.89| 0.13±0.038      | 29±4.3 |

There is high confidence that emission growth has been varied, but persistent across different groups of gases. Decade-by-decade increases in global average annual emissions have been observed consistently across all (groups of) greenhouse gases (Table 7), apart from CO₂-LULUCF emissions, which have been more stable, albeit uncertain, and only recently started to show an upward trend. The pace and scale of emission growth has varied across groups of gases. While average annual
emissions of all greenhouse gases together grew by about 70% from 32±4.3 GtCO$_2$eqyr$^{-1}$ during the 1970s (1970-1979) to 56±6.0 GtCO$_2$eqyr$^{-1}$ during the 2010s (2010-2019). CO$_2$-FFI emissions doubled from 18±1.4 to 36±2.9 GtCO$_2$eqyr$^{-1}$ and F-gases grew more than sevenfold from 0.17±0.052 to 1.4±0.41 GtCO$_2$eqyr$^{-1}$ across the same time period. In fact, persistent and fast growth in F-gas emissions has resulted in emissions levels that are now tracking at about 1.6±0.49 Gt CO$_2$eqyr$^{-1}$ in 2019 – 2.8% of total GHG emissions measured as GWP-100. Increases in average annual emissions levels from the 1970s (1970-1979) to the 2010s (2010-2019) were lower for CO$_2$-LULUCF (24%), CH$_4$ (42%) as well as N$_2$O (44%) (see Table 7).

However, there is low confidence that the reported increases in CO$_2$-LULUCF emissions by decade actually constitute a statistically robust trend given the large uncertainties involved. In fact, two bookkeeping models underlying the AFOLU data show opposing positive and negative trends (BLUE, H&N, respectively), while the third model (OSCAR), averaging over simulations that use either the same land-use forcing as BLUE (LUH2) or H&N (FAO), tracks the approximate mean of these (see also Section 3.2). Dynamic global vegetation models, which also use the LUH2 forcing, show higher estimates recently, explained by them considering the loss in sink capacity, while the bookkeeping models do not (see Figure 1). Overall, the different lines of evidence are inconclusive with regard to an upward trend in CO$_2$-LULUCF emissions.

Global anthropogenic greenhouse gas emissions grew continuously slower than world GDP across all (groups of) individual gases resulting in a sustained decline in the GHG intensity of GDP as shown in Figure 5. The only exception is the group of F-gases for which the GHG intensity of GDP has increased year-by-year until 2010 (with a marked acceleration during the 2000s) and started declining thereafter. Per capita GHG emissions have been fluctuating substantially, with a sustained decline in global per capita GHG emissions since the 1970s followed by an approximate 15 year period of continued growth from the 2000s. In recent years, per capita GHG emissions levels have stabilized without clear evidence for peaking. For CO$_2$-FFI emissions, sustained growth in per capita emissions can be observed since the mid-1990s levelling off during the last decade. Per capita emissions for CO$_2$-LULUCF, CH$_4$ and N$_2$O declined consistently since the 1970, but this trend has flattened out since the mid-1990s or early 2000s. Per-capita F-gas emissions show sustained and rapid growth until 2010 and have stabilized since.
The continuous growth in global anthropogenic GHG emissions since the 1970s was mainly driven by activity growth in three major sectors: energy supply, industry and transportation (see Table SM-2; Fig. SM-4). In energy supply and transportation, average annual emissions were about 2.3 times larger for 2010-2019 than for 1970-1979, growing from 8.5 to 19 GtCO$_2$eqyr$^{-1}$ and 3.5 to 8.1 GtCO$_2$eqyr$^{-1}$, respectively. In industry, average annual GHG emissions were 1.9 times larger growing from 7.3 GtCO$_2$eqyr$^{-1}$ in 1970-1979 to 14 GtCO$_2$eqyr$^{-1}$ in 2010-2019. At the sub-sector level, electricity & heat and road transport are the largest segments, growing 2.9 and 2.6 times between 1970-1979 and 2010-2019, respectively, from an average 4.6 to 14 GtCO$_2$eqyr$^{-1}$, and 2.2 to 5.8 GtCO$_2$eqyr$^{-1}$. The fastest growing sub-sector has been process emissions from cement, which is 4 times larger in 2010-2019 compared to 1970-1979, and currently accounts for an average 1.4 GtCO$_2$eqyr$^{-1}$. Other rapidly expanding sectors are international aviation (2.9 times larger on 1970-1979 levels), chemicals (2 times larger), metals (1.8 times larger) and waste (1.8 times larger). Growth in GHG emissions in AFOLU and buildings has been much more moderate with average annual GHG emissions only about 25% and 10% higher for 2010-2019 than for 1970-1979.

Most GHG emissions growth occurred in Asia and Developing Pacific as well as the Middle East, where emissions more than tripled from 6.4 GtCO$_2$eqyr$^{-1}$ and 0.8 GtCO$_2$eqyr$^{-1}$ in 1970-1979 to 23 GtCO$_2$eqyr$^{-1}$ and 2.9 GtCO$_2$eqyr$^{-1}$ in 2010-2019, respectively (see Table SM-1). Over the same time period GHG emissions grew 2.2 times in Africa and 1.7 times in Latin America and the Caribbean, while average annual anthropogenic GHG emissions levels in developed countries and Eastern Europe and West-Central Asia remained stable. However, Figure 6 highlights important variability: first, GHG emissions growth is taking place against the background of large differences in per capita GHG emissions between and within regions.

For example, GHG emissions in developed countries have stabilized at high levels of per capita emissions compared to most other regions. Similarly, some countries in the Middle East are among the largest GHG emitters in per capita terms, while other countries of the region such as Yemen have seen comparatively little economic development showing low levels of per capita emissions. Second, the growth in GHG emissions has also been highly varied. For example, several developed countries in Europe such as UK, Germany or France have lower GHG emissions levels today than in the 1970s. In other countries like the US GHG emission levels are still considerably higher today even though they have recently started reducing GHG emissions – unlike Australia or Canada, which have until now only begun stabilizing their GHG emission levels. A comprehensive assessment of country progress in reducing GHG emissions can be found in Lamb et al. (2021b).
Figure 6 – Levels of and changes in GHG emissions by country. Aggregate GHG emissions are reported in GtCO$_2$eq converted based on global warming potentials with a 100-year time horizon (GWP-100) from the IPCC Fifth Assessment Report (Myhre et al., 2013). Panel a shows per capita GHG emission levels (tCO$_2$eq/cap) for the year 2019 using UN population data for normalization (World Bank, 2021). Panel b shows average annual changes (in %) in GHG emissions by countries for 2010-2019. Panel c shows average annual changes (in %) in GHG emissions by countries for 1970-2019.
In Fig. 7 we compare historic GHG emission trends with different scenarios, to explore how emissions are developing relative to the range of projected future outcomes. The Integrated Assessment Modelling (IAM) community quantified five Shared Socioeconomic Pathways (SSPs) for different levels of radiative forcing in 2100 using six different IAMs (Riahi et al., 2017; Rogelj et al., 2018b). The SSPs are grouped according to their radiative forcing ranging from 1.9 Wm$^{-2}$ to 8.5 Wm$^{-2}$, aimed at spanning the full range of potential outcomes. The Coupled Model Intercomparison Project Phase 6 (CMIP6) took a subset of these quantified SSPs as the basis for future climate projections (Gidden et al., 2019; O’Neill et al., 2016). In recent years, the use of the very high forcing scenarios – particularly SSP5-8.5 - is being debated in the scientific community (e.g. Hausfather and Peters, 2020b, 2020a; Pedersen et al., 2020; Schwalm et al., 2020).

Historical GHG emissions from our database are consistent with the levels and trends in the scenario data, despite the scenarios being calibrated on older data sources (Gidden et al., 2019) – mainly CEDS (Hoesly et al., 2018). The observed differences are larger for the GHGs with the highest uncertainty, notably CO$_2$-AFOLU, N$_2$O and F-gas emissions (Sections 3.2, 3.4 and 3.5). Across the different GHGs, historical emissions track on aggregate with the higher forcing scenarios such as the SSP3-7.0 and SSP5-8.5 markers, in terms of both levels and growth rates. CO$_2$-FFI emissions still tend towards the higher end of the scenario range shown here, but there are signs that CO$_2$-FFI emissions are slowing to more moderate forcing levels (e.g., SSP4-6.0 and SSP2-4.5) when considering recent trends (Hausfather and Peters, 2020a). CH$_4$ and N$_2$O emissions sit more in the middle and at the lower-end of the scenario range – the latter driven by the lower levels of N$_2$O emissions in EDGAR – and F-gases are consistent with the scenarios. Total GHG emissions track the higher end scenarios.

Figure 7 highlights the very different future emission trajectories envisioned by IAMs for individual gases – particularly at radiative forcing levels that are consistent with the goal of the Paris Agreement such as SSP1-2.6 and SSP1-1.9. In contrast to CO$_2$ emission, non-CO$_2$ forcers such as anthropogenic CH$_4$ and N$_2$O emissions are not reduced to zero. However, in many scenarios, F-gases reach zero emissions. N$_2$O emissions remain at similar levels to today in some of the scenarios with a 1.9 Wm$^{-2}$ forcing at the end of the century, while they are about halved in others. Reductions in methane emissions are a bit more pronounced ranging from about 100 to 200 MtCH$_4$yr$^{-1}$ in 2100 compared to almost 400 MtCH$_4$yr$^{-1}$ in 2019. CO$_2$-AFOLU emission trajectories overlap for different forcing levels, partly reflecting the complexities of modelling land-use change, but overall show a tendency towards a net carbon sink even in SSPs with little or even without climate policy. Given recent trends in land-use change emissions, it could be questioned whether the scenarios adequately explore the uncertainty in future land-use change emissions (Hausfather and Peters, 2020b).
Figure 7 - Historical emissions of GHGs and future projections in socio-economic scenarios. The historical emissions are from this dataset. The Shared Socioeconomic Pathways (SSPs) are from the SSP database version 2 (Riahi et al., 2017; Rogelj et al., 2018b). See also: https://tntcat.iiasa.ac.at/SspDb/). Highlighted scenarios are the markers used in CMIP6 (O’Neill et al., 2016) after harmonisation (Gidden et al., 2019).
4.1.2 - Global greenhouse gas emissions for the last decade 2010-2019

There is high confidence that global anthropogenic GHG emission levels were higher in 2010-2019 than in any previous decade and GHG emissions levels have grown across the most recent decade. Average annual GHG emissions for 2010-2019 were 56±6.0 GtCO$_2$eq yr$^{-1}$ compared to 47±5.4 and 39±4.9 GtCO$_2$eq yr$^{-1}$ for 2000-2009 and 1990-1999, respectively. In 2019 GHG emissions were about 6.8±1.0 GtCO$_2$eq yr$^{-1}$ or 13% higher than in 2010. F-gas and CO$_2$-LULUCF emissions were 50% and 24% higher in 2019 than in 2010 compared to 12%, 11% and 9% for N$_2$O, CO$_2$-FFI and CH$_4$ emissions, respectively. CO$_2$ emissions from FFI contributed 3.8±0.3 of the 6.8±1.0 GtCO$_2$eq yr$^{-1}$ increase in annual GHG emissions with additional contributions of 1.3±0.89 GtCO$_2$eq yr$^{-1}$ from CO$_2$-LULUCF, 0.93±0.28 GtCO$_2$eq yr$^{-1}$ from CH$_4$, 0.25±0.15 GtCO$_2$eq yr$^{-1}$ from N$_2$O and 0.55±0.16 GtCO$_2$eq yr$^{-1}$ from F-gases. While average annual greenhouse gas emissions growth slowed between 2010-2019 compared to 2000-2009 from 2.4% to 1.1%, the absolute increase in average decadal GHG emissions by 9.4±0.77 GtCO$_2$eq yr$^{-1}$ from the 2000s to the 2010s has been the largest since the 1970s – and probably within all human history as suggested by available long-term data (e.g. Friedlingstein et al., 2020; Hoesly et al., 2018).

About 50% of the recent growth in global GHG emissions between 2010 and 2019 came from China (2.7 GtCO$_2$eq yr$^{-1}$) and India (0.94 GtCO$_2$eq yr$^{-1}$) (Figure 8). Among the major emitters, fastest GHG emissions growth was observed for Vietnam with average annual rates of 5.1% yr$^{-1}$ between 2010 and 2019 followed by Turkey (4.6% yr$^{-1}$), Indonesia (3.8% yr$^{-1}$), Pakistan (3.4% yr$^{-1}$), India (3.2% yr$^{-1}$), Saudia Arabia (2.8% yr$^{-1}$) and China (2.4% yr$^{-1}$). GHG emission reductions achieved by countries over the last decade are comparatively small even though there is a growing number of countries on sustained emissions reductions trajectories (Lamb et al., 2021b; Le Quéré et al., 2019b). The US showed the largest net anthropogenic GHG emissions reductions of 0.21 GtCO$_2$eq yr$^{-1}$ between 2010 and 2019 even though more significant reductions in CO$_2$ emissions of 0.46 GtCO$_2$yr$^{-1}$ from a switch from coal to gas in the context of the shale gas expansion was partially compensated by additional CH$_4$ (0.12 GtCO$_2$eq yr$^{-1}$) and F-gas (0.13 GtCO$_2$eq yr$^{-1}$) emissions (Figure 8). Other countries with decreasing GHG emission levels were Germany (0.13 GtCO$_2$eq yr$^{-1}$) and the United Kingdom (0.14 GtCO$_2$eq yr$^{-1}$), where the latter shows the fastest average annual reductions at a rate of 2.6% yr$^{-1}$ in the sample – in line with some GHG emission reduction scenarios that limit global warming to well below 2°C, but those ones that tend to rely more heavily on carbon dioxide removal technologies (Hilaire et al., 2019; Streffler et al., 2018). Further information on country contributions to GHG emission changes since 1990s – an important reference for UN climate policy – are shown in supplementary Fig. SM-2.

Official statistics submitted annually by 43 countries listed in Annex I of the Kyoto Protocol (see Fig. 9) to the UNFCCC (hereafter UNFCCC-CRFs) indicate 1.9% lower emissions over the period 1990-2019. The vast majority of the Annex I countries, which contributed 33.6% of the global GHG emissions in 2019 (according to the dataset presented in this paper), report lower total GHG emissions in 2019 and lower growth (higher reduction) rates between 1990-2019 as compared with the data presented here. The total emissions of the Annex I countries in 2019 stand with 16.8 GtCO$_2$eq yr$^{-1}$ according to the
national inventories 5.6% lower than the data presented here for the same countries. The growth rates over the last decade (2010-2019) reported in the national inventories was on average 0.3 percentage points lower than the growth rates for the same set of countries in our dataset (see Figure 8). Additional analysis comparing our data with UNFCCC-CRF inventories for individual (groups of) gases and countries is provided in supplementary Fig. SM-3.

Sectoral GHG emissions were either stable or increased between 2010 and 2019. There is high confidence that no substantive GHG emissions reductions were observable for entire sectors at the global level (Fig. 8 d and e). The largest sectoral contribution to the 6.8±1.0 GtCO₂eqyr⁻¹ increase in GHG emissions levels between 2010 and 2019 was from CO₂-AFOLU with about 1.3 GtCO₂yr⁻¹, but this estimate is much more uncertain compared to other sectors. The continued expansion of fossil-fuel based electricity production increased CO₂ emissions by about 1.2 GtCO₂yr⁻¹ closely followed by CO₂ emissions from road transport (0.9 GtCO₂yr⁻¹) and metal production (0.7 GtCO₂yr⁻¹) – the latter being the fastest large emission source in relative terms with 2.1%. Domestic and international aviation are the most rapidly growing sectors (3.8% and 3.7%, respectively), but remain globally small sources of emissions growth (0.1 and 0.17 GtCO₂yr⁻¹). Emissions from chemical production and waste treatment are also sizable and comparatively fast growing, contributing 0.47 GtCO₂yr⁻¹ at 1.9%yr⁻¹ and 0.31 GtCO₂yr⁻¹ at 1.6%yr⁻¹, respectively.
Panel a: Aggregate GHG emission trends by groups of gases reported in GtCO₂eq converted based on global warming potentials with a 100-year time horizon (GWP-100) from the IPCC Fifth Assessment Report (Myhre et al., 2013). Average annual growth rates by decade are reported at the top of the figure (in %yr⁻¹). Waterfall diagrams juxtaposes GHG emissions for the most recent year 2019 in CO₂ equivalent units using GWP-100 values from the IPCC’s Second and Fourth Assessment Report, respectively. Error bars show the associated uncertainties at a 90 % confidence interval. Panels b and c show relative (in %) and absolute (in GtCO₂eq) changes in GHG emissions for a selection of the largest emitting countries excluding CO₂-LULUCF emissions as uncertainties in our estimates are too high for country-level reporting. The yellow dots represent the emissions data according to the national inventories reported by the Annex I countries of the Kyoto Protocol to the UNFCCC (Gütschow et al., 2021; Louise Jeffery et al., 2018). Panels d and e show relative (in %) and absolute (in GtCO₂eq) changes in GHG emissions for a selection of the largest emitting sectors (see Table 2).

4.1.3 Global greenhouse gas emissions in 2019

Global net anthropogenic greenhouse gas emissions continued to grow and reached 59±6.6 GtCO₂eq in 2019 (Figure 8). In 2019, CO₂ emissions from FFI were 38±3.0 Gt, CO₂ from LULUCF 6.6±4.6 Gt, CH₄ 11±3.3 GtCO₂eq, N₂O 2.4±1.5 GtCO₂eq and F-gases 1.6±0.49 GtCO₂eq. Of the 59±6.6 GtCO₂eq emissions in 2019, 33% (20 GtCO₂eqyr⁻¹) were from energy supply, 24% (15 GtCO₂eqyr⁻¹) from industry, 22% (20 GtCO₂eqyr⁻¹) from AFOLU, 15% (8.7 GtCO₂eqyr⁻¹) from transport, and 5.6% (3.3 GtCO₂eqyr⁻¹) from buildings. In 2019, the largest absolute contributions in GHG emissions were from Asia and Developing Pacific (43%), Developed countries (25%) and Latin America and the Caribbean (10%). China (14 GtCO₂eqyr⁻¹), USA (6.5 GtCO₂eqyr⁻¹) and India (3.7 GtCO₂eqyr⁻¹) and the Russian Federation (2.5 GtCO₂eqyr⁻¹) remained the largest country contributors to global GHG emissions, excluding CO₂-LULUCF as we do have not sufficient confidence to report this data at the country level.

In 2019, emissions were 1.4 GtCO₂eqyr⁻¹ or 2.4% higher than the 58±6.1 GtCO₂eq in 2018. Most of this growth (~0.9±0.6 GtCO₂eqyr⁻¹) is related to increases in CO₂-LULUCF, which results in particular from the high peat and tropical deforestation/degradation fires as outlined in Friedlingstein et al. (2020). Growth in CO₂-FFI was very modest at 0.28±0.023 GtCO₂yr⁻¹ (Δ0.8%), while F-gas, N₂O and methane grew more rapidly by 3.8%, 1.2% and 1.0% - but at much lower absolute levels. While the rate of GHG emissions change between 2018 and 2019 is numerically comparable with the period of high GHG emissions growth during the 2000s, there is low confidence in the reported value due to the high share of CO₂-LULUCF emissions, which are highly uncertain, and the preliminary nature of the underlying land-use data for 2019 and temporal extrapolation of two of the three bookkeeping estimates. Moreover, given prevailing uncertainties there is low confidence that GHG emissions have never been higher than in 2019 as suggested by the data, but high confidence that average annual GHGs emissions have never been higher for a decade than in 2010-2019 (see Friedlingstein et al., 2020; Hoesly et al., 2018).
Discussion

In this article we provide a comprehensive, detailed dataset for global, regional, national and sectoral GHG emissions from anthropogenic sources covering the last five decades (1970-2019) built from the EDGARv6 GHG emissions inventory, a fast-track update/projection as well as data on CO2-LULUCF emissions from global bookkeeping models. We assess uncertainties in our estimates by combining statistical analysis of the underlying data and expert judgement based on an in-depth review of the literature by each gas. We report uncertainties at a 90% confidence interval (5th-95th percentile range). This differs to the uncertainty reported by the Global Carbon Project for the global carbon, methane or nitrous oxide budgets (Friedlingstein et al., 2020; Saunois et al., 2020; Wang et al., 2020), because uncertainties in our dataset are comparatively well characterized (Janssens-Maenhout et al., 2019; Solazzo et al., 2021).

Our uncertainty assessment is broadly consistent with previous assessments focussing on all GHGs (Blanco G. et al., 2014; UNEP, 2020), but we provide some important updates. Our evidence-informed uncertainty judgements are higher for CO2-LULUCF (±70% rather than ±50%) and CH4 (±30% rather than ±20%) drawing from work on global carbon (Friedlingstein et al., 2020) and methane (Saunois et al., 2020) budgets. We recognize the vast divergence between bottom-up inventory estimates and top-down atmospheric measurements for individual F-gases. Our revised uncertainty estimate for aggregate F-gas emissions of ±30% (rather than ±20%) reflects the smaller aggregate deviation when all individual species are considered together.

Our analysis involves aggregating GHG emissions into a single unit using GWP-100 values from IPCC AR5 (without carbon cycle feedbacks). By doing so we follow the practice taken in UNFCCC climate diplomacy and large parts of the literature on climate change mitigation. However, we recognise intense scientific and academic debates about the aggregation of GHGs into a single unit and alternative choices of metrics (Myhre et al., 2013) (see Section 3.7). We therefore also use a simple climate model to assess the warming contribution by the individual groups of gases and find that for the historical period when emissions are growing, the GWP-100 gives a reasonable approximation to the warming contributions, but this is not expected to hold when emissions change trajectory under mitigation. In the absence of comprehensive uncertainty analysis that covers CO2-LULUCF as well as F-gas emissions, we estimate the overall uncertainties of aggregated GHG emissions by simply adding the individual uncertainties judgements by (groups of) gases in quadrature under the assumption of their independence. Comprehensive uncertainty analysis of EDGAR data covering all greenhouse gases should be performed in the future, building on Solazzo et al. (2021). For the first time, we also provide an initial estimate of metric uncertainty arising from the aggregation of individual greenhouse gases into a single unit (see Section 3.7).

Our assessment highlights the comprehensive nature of our dataset covering anthropogenic sources of greenhouse gas emissions. However, there are still some important data gaps. Most recent and comprehensive assessments of the methane
(Saunois et al., 2020) and nitrous oxide (Tian et al., 2020) budgets suggest that anthropogenic CH$_4$ and N$_2$O emissions could be 10-20% higher than reported in EDGAR, respectively. F-gas emissions estimates for individual species in EDGARv5 do not align well with atmospheric measurements and the F-gas aggregate over-reports the measured concentrations by about 30%. However, EDGAR and official national emission reports under the UNFCCC do not comprehensively cover all relevant F-gases species. We also note that our data does not cover species such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) or NF$_3$ and show that those species, which are regulated under the Montreal Protocol (except NF$_3$), have contributed more to CO$_2$eq emissions as well as observed warming. There is an urgent need to dedicate more resources and attention to the independent improvement of F-gas emission statistics, recognizing these current shortcomings and their increasingly important role as a driver of warming.

Our analysis of global, anthropogenic GHG emission trends over the past five decades (1970-2019) highlights a pattern of varied, but sustained emissions growth. There is high confidence that global anthropogenic greenhouse gas emissions have increased every decade. Emission growth has been varied, but persistent across different (groups of) gases. While CO$_2$ has accounted for almost 75% of the emission growth since 1970 in terms of CO$_2$eq as reported here, the combined F-gases have grown much faster than other GHGs, albeit starting from very low levels. Today, they make a non-negligible contribution to global warming – recognizing that important species such as CFCs and HCFCs are even not considered. There is further high confidence that global anthropogenic GHG emissions levels were higher in 2010-2019 than in any previous decade and GHG emissions levels have grown across the most recent decade. While average annual greenhouse gas emissions growth slowed between 2010-2019 compared to 2000-2009, the absolute increase in average decadal GHG emissions from the 2000s to the 2010s has been the largest since the 1970s – and within all human history as suggested by available long-term data (e.g. Friedlingstein et al., 2020; Hoesly et al., 2018). We note considerably higher rates of change in GHG emissions between 2018 and 2019 than for the entire decade 2010-2019, which is numerically comparable with the period of high GHG emissions growth during the 2000s, but we place low confidence in this value as the majority is driven by highly uncertain increases in CO$_2$-LULUCF emissions as well as the use of preliminary data and extrapolation methodologies for these most recent years. While there is a growing number of countries today on a sustained emission reduction trajectory (Lamb et al., 2021b; Le Quéré et al., 2019a), it is important to study the drivers of these reductions as well as patterns of emission growth in other parts of the world (Lamb et al., 2021a). Our analysis further reveals that there are no global sectors that show sustained reductions in GHG emissions.

There is a growing availability of global datasets on anthropogenic emissions sources over the last 10-20 years. However, such global emission inventories have to rely on relatively simple Tier-1 estimation methods and few use more complex Tier-2 methods. Comparison of our estimates with Tier-2 and Tier-3 UNFCCC-CRFs by Annex I countries shows considerable discrepancies for some gases. On aggregate, there is a clear trend towards smaller values for GHG emission reductions and larger values for GHG emission increases in our dataset. Further work needs to be done to fully appreciate underlying
differences (Andrew, 2020a; Petrescu et al., 2020c, 2020b). Figure 9 further highlights the lack of recent official GHG emissions inventories for many non-Annex 1 countries outside those global emission inventories. Despite the importance of high-quality emission statistics for climate change research and tracking progress in climate policy, our analysis here emphasises considerable prevailing uncertainties and the need for improvement in emission reporting. In sectors where production efficiencies are changing rapidly, as is often the case in developing countries, using emission estimates based on Tier-1 methodologies is likely to mischaracterise trends as both activity data and emission factors change over time (Wilkes et al., 2017). Moving confidently towards net-zero emissions requires high quality emissions statistics for tracking countries’ progress based at least on Tier-2, if not on complex Tier-3 estimation models using comprehensive, country-specific activity data and emissions factors (IPCC, 2019). This would also support the formulation of more nuanced climate policy goals that reflect changes in emissions intensity as entry points for more comprehensive and ambitious targets to reduce absolute emissions. However, underpinning such approaches with robust evidence requires the collection of a range of country-specific activity data and development of adequate statistical infrastructure for all countries of the world (FAO and GRA, 2020). Making progress in the implementation of the Paris Agreement and keeping warming well below 2°C requires dedication and cooperation between countries: working together on a robust evidence base in GHG emissions reporting provides one important and often underappreciated step.
Figure 9 - Overview of most recent GHG emission inventories submitted to the UNFCCC: The map captures the last year for which emission inventories were conducted and published by the UNFCCC on their website (as of 31 May 2021). Annex I countries, according to the UNFCCC definition, have reported their last inventories for 2019. Non-Annex I countries should in principle submit national inventories every two years according to the Paris Agreement. Updated from Janssens-Maenhout et al. (2019)
Data availability
The emissions dataset used for this study (Minx et al. 2021) is available at https://doi.org/10.5281/zenodo.5053056.

[NOTE TO REVIEWERS: Data on CO₂ emissions from fossil fuel combustion and industry, methane emissions and nitrous oxide emissions are from the most recent EDGARv6 data. As EDGARv6 data is still being compiled for F-gases, this manuscript contains EDGARv5 estimates for these, but we will update to EDGARv6 during the revision process. This procedures has been agreed upon with David Carlson – one of the chief editors of the journal – before manuscript submission]

Author contributions
JCM and WFL designed the research. WL, ND, RMA, GPP, MR and PMF generated the figures with support by all other authors (JCM, JGC, MC, DG, JO, JP, AR, MS, SJS, ES, HT). WFL, ND, RMA, GPP, MR and PMF carried out the required computations. JCM led on the analysis in collaboration with all authors (WFL, RMA, JGC, MC, ND, PMF, DG, JO, GPP, JP, AR, MR, MS, SJS, ES, HT). JCM led on the writing of the manuscript in collaboration with all authors (WFL, RMA, JGC, MC, ND, PMF, DG, JO, GPP, JP, AR, MR, MS, SJS, ES, HT).

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