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

Jan C. Minx[1,2,*], William F. Lamb[1,2,*], Robbie M Andrew[3], Josep G. Canadell[4], Monica Crippa[5], Niklas Döbbeling[1], Piers M. Forster[2], Diego Guizzardi[4], Jos Olivier[6], Glen P. Peters[3], Julia Pongratz[7,8], Andy Reisinger[9], Matthew Rigby[10], Marielle Saunois[11], Steven J. Smith[12], Efisio Solazzo[5], Hanqin Tian[13]

[1] Mercator Research Institute on Global Commons and Climate Change, Berlin, 10827, Germany
[2] Priestley International Centre for Climate, School of Earth and Environment, University of Leeds, Leeds; LS2 9JT, UK
[3] CICERO Center for International Climate Research, Oslo, 0318 Norway
[4] Global Carbon Project, CSIRO Oceans and Atmosphere, Canberra, Australia
[5] European Commission, Joint Research Centre, Ispra, Italy
[6] PBL Netherlands Environmental Assessment Bureau, the Hague, the Netherlands
[7] Ludwig-Maximilians-Universität München, Luisenstr. 37, 80333 Munich, Germany
[8] Max Planck Institute for Meteorology, Bundesstrasse 53, 20146 Hamburg, Germany
[9] Institute for Climate, Energy and Disaster Solutions, Fenner School of Society & Environment, Building 141, Linnaeus Way, The Australian National University, Canberra, ACT, 2600, Australia
[10] School of Chemistry, University of Bristol, Bristol, BS8 1TS, UK
[11] Laboratoire des Sciences du Climat et de l'Environnement, LSCE-IPSL (CEA-CNRS-UVSQ), Université Paris-Saclay 91191 Gif-sur-Yvette, France
[12] Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD 20740 USA
[13] International Center for Climate and Global Change Research, School of Forestry and Wildlife Sciences, Auburn University, Auburn, AL 36849, USA
[*] *Correspondence to*: Jan C. Minx (minx@mcc-berlin.net) and William F. Lamb (lamb@mcc-berlin.net)

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 CO_2 emissions from fossil fuel combustion and industry (FFI), CH_4 emissions, N_2O 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 CO_2 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: CH_4 and N_2O 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

40   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

45   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-

50   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

55   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

60   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

65   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
70   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 (CO_2) emissions well within the
21st century along with deep reductions in non-CO_2 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.

75

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
80   provide sectoral detail and particularly for non-CO_2 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).

85

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 CO_2 emissions from fossil fuel combustion and industry (FFI),
CH_4 emissions, N_2O emissions, and fluorinated gases (F-gases). We use a well-established fast-track method to extend this
90   dataset to 2019 (Crippa et al., 2020, 2021). For completeness we add net CO_2 emissions from land use, land-use change and
forestry (CO_2-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.

95

Table 1 – Overview of global inventories of GHG emissions

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	CO_2-FFI, CH_4, N_2O	208 countries; global	5 main sectors	1970-2019 for CO2; 1970-2015 for other GHG		IEA, BP, USGS, IFA, GGFR/NOAA, 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	CO_2-FFI, CH_4, N_2O	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	SO_2, NO_x, BC, OC, NH_3, NMVOC, CO, CO_2, CH_4, N_2O	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	CO_2, CH_4, N_2O, NO_x, CO, NMVOC, SO_2	Parties included in Annex I to the Convention	Energy, industry, agriculture, LULUCF, waste	1990-2018		Country inventory submissions		https://unfccc.int/ghg-inventories-annex-i-parties/2021
Global Carbon Budget	GCP	2020	CO_2-FFI, CO_2-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/10.18160/GCP-2020

						forcing data			
Global, Regional, and National Fossil-Fuel CO2 Emissions	CDIAC-FF	V2017	CO_2-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		CO_2-FFI	230 countries, global	3 fuel types	1980-2018; 1949-2018 (global)			https://www.eia.gov/international/data/world
BP Statistical Review of World Energy	BP	2020 | 69th edition	CO_2-FFI	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		CO_2-FFI	190 countries	3 fossil fuels, 6 sectors	1971-2019; OECD: 1960-2019	2006 GLs for National Greenhouse Gas Inventories		https://webstore.iea.org/co2-emissions-from-fuel-combustion-2019-highlights
PKU-FUEL			CO_2, CO, $PM_{2.5}$, PM_{10}, TSP, BC, OC, SO_2, NO_x, NH_3, PAHs		6 sectors, 5 fuel types,	1960-2014			http://inventory.pku.edu.cn/
Carbon Monitor			CO_2-FFI	11 countries, global	6 sectors	2019-	EIA, EDGAR, GCP	Liu et al. (2020)	https://carbonmonitor.org/
Bookkeeping of land-use emissions	BLUE		CO_2-LULUCF			1500-2012	LUH2 land-use forcing data	Hansis et al. (2015)	https://doi.org/10.18160/GCP-2020
OSCAR – an Earth system	OSCAR		CO_2-LULUCF			1750-2010	FAO/FRA and LUH2 land-use	Gasser et al. (2017, 2020)	https://doi.org/10.18

compact model						forcing data		160/GCP-2020v
Houghton and Nassikas Bookkeeping Model	H&N	CO$_2$-LULUCF			1850-2015	FAO/FRA land-use forcing data	Houghton and Nassikas (2017)	https://doi.org/10.18160/GCP-2020
The Greenhouse gas – Air pollution INteractions and Synergies Model	GAINS	CO$_2$, CH$_4$, N$_2$O, F-gases	83 countries/regions				Höglund-Isaksson (2012)	
EPA-2020: Greenhouse gas emission inventory	US-EPA	CO$_2$, CH$_4$, N$_2$O, 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	N$_2$O	10 land regions and 3 oceanic regions	21 natural and human sectors	1980-2016	FAOSTAT, GAINS, EDGAR	Tian et al. (2020)	https://www.globalcarbonproject.org/nitrousoxidebudget/
FAOSTAT inventory		2020	CO$_2$, CH$_4$, N$_2$O, F-gases	Global (198 countries)	4 agricultural sectors	1990-2017	PRIMAP-hist	Frederici et al. (2015), Tubiello et al. (2013), Tubiello (2019)	http://www.fao.org/faostat/en/#data/EM/metadata
Fire Inventory from NCAR	FINN	CO$_2$, CH$_4$, N$_2$O	Global				Wiedinmyer et al. (2011)	
Global fire assimilation system	GFAS	CO$_2$, CH$_4$, N$_2$O	Global				Kaiser et al. (2012)	
Global fire emissions database	GFED	CO$_2$, CH$_4$, N$_2$O	Global				Giglio et al. (2013)	
Quick fire emissions dataset	QFED	CO$_2$, CH$_4$, N$_2$O	Global				Darmenov and da Silva (2015)	

2 Methods and Data

2.1 Overview

100   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

105   forestry (CO_2-LULUCF); (3) methane emissions (CH_4); (4) nitrous oxide emissions (N_2O); (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

110   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

115   the two years and then normalizing to the emissions in the first year: $((E_{(t0+1)}-E_{t0})/E_{t0})\times100$. 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).

120

  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_2O emissions for 2019 as well as 2016-2019 for F-gas emissions based on Olivier et al.

125   (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). As shown in

Table 2, sectoral detail is organised along five major economic sectors as is common in IPCC reports on climate change
130 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.

135

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 CO_2 and CH_4 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.i (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.b (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 fugitive emissions	1.B.1.a (fossil), 1.B.1.c (fossil)	CO2, CH4
	Electricity & heat	1.A.1.a.i (fossil), 1.A.1.a.ii (fossil), 1.A.1.a.iii (fossil)	CO2, CH4, N2O
	Oil and gas fugitive emissions	1.B.2.a.iii.2 (fossil), 1.B.2.a.iii.3 (fossil), 1.B.2.a.iii.4 (fossil), 1.B.2.b.iii.2 (fossil), 1.B.2.b.iii.4 (fossil), 1.B.2.b.iii.5 (fossil), 1.B.2.b.iii.3 (fossil), 1.B.2.b.ii (fossil), 1.B.2.a.ii (fossil)	CO2, CH4, N2O
	Other (energy systems)	1.A.1.c.ii (fossil), 1.A.1.c.i (fossil), 1.A.4.c.i (fossil), 1.A.5.a (fossil), 2.G.1.b (fossil), 5.B (fossil), 5.A (fossil)	CO2, CH4, N2O, SF6
	Petroleum refining	1.A.1.b (fossil)	CO2, CH4, N2O

Industry	Cement	2.A.1 (fossil)	CO2
	Chemicals	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
	Metals	1.A.1.c.i (fossil), 1.A.1.c.ii (fossil), 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
	Other industry	1.A.2.d (bio), 1.A.2.d (fossil), 1.A.2.e (bio), 1.A.2.e (fossil), 1.A.2.f (bio), 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, c-C4F8, C2F6, C3F8, C4F10, C6F14, C7F16, CF4, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-23, HFC-236fa, HFC-245fa, HFC-32, HFC-365mfc, HFC-43-10-mee, SF6
	Waste	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)

140

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:

145

150

$$EM_i(C, t, x) = \sum_{j,k} \left[AD_i(C,t) \cdot TECH_{i,j}(C,t) \cdot EOP_{i,j,k}(C,t) \cdot EF_{i,j}(C,t,x) \cdot \left(1 - RED_{i,j,k}(C,t,x) \right) \right]$$

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 CH_4 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 CO_2-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 (CH$_4$) as well as UNFCCC-CRF data for Annex I countries on coal production (CH$_4$ recovery) and the production of chemicals (N$_2$O 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 CO$_2$ emissions Land Use, Land-Use Change and Forestry (CO$_2$-LULUCF)

We consider all fluxes of CO_2 from land use, land-use change and forestry. This includes CO_2 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_2O 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 – CO_2, CH_4, N_2O 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,

215 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-

220 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

225 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

230 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 N_2O discussion below). Independent top-down observational constraints are, therefore, particularly useful to bound total emission estimates (Petrescu et al., 2020c, 2020b).

235 Solazzo et al. (2021) evaluated the uncertainty of the EDGAR's source categories and their totals for all the main GHGs (CO_2-FFI, CH_4, N_2O). 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.

240 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.

245 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.

250 We adopt a 90% confidence interval (5th-95th 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

255 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_2 emissions from fossil fuels and industrial processes

Several studies have compared estimates of annual CO_2-FFI emissions from different global inventories (Andres et al., 2012;
260 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_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
265 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

270   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-CO₂ 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 CO₂ 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 CO₂-FFI emissions track at 34.4±2 GtCO₂ 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 CO₂-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 CO₂ 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-CO₂ emissions across different version of the EDGAR dataset are shown in the Supplementary Material (see Fig. SM-1).

290 Uncertainties in CO_2-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. CO_2-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

295 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 CO_2 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

300 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 CO_2 uptake at 0.70 $GtCO_2$ for 2010-2019 (Friedlingstein et al., 2020).

Uncertainties of energy consumption data (and, therefore, CO_2-FFI emissions) are generally higher for the first year of their

305 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).

310 Example estimates of uncertainties for CO_2 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 CO_2-FFI emissions before the 1970s are higher than for more recent estimates. Over the last two to three

315 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 CO_2-FFI emissions estimates within one standard deviation (1σ) as ±5% (±10% at 2σ). This is broadly consistent

320 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).

325

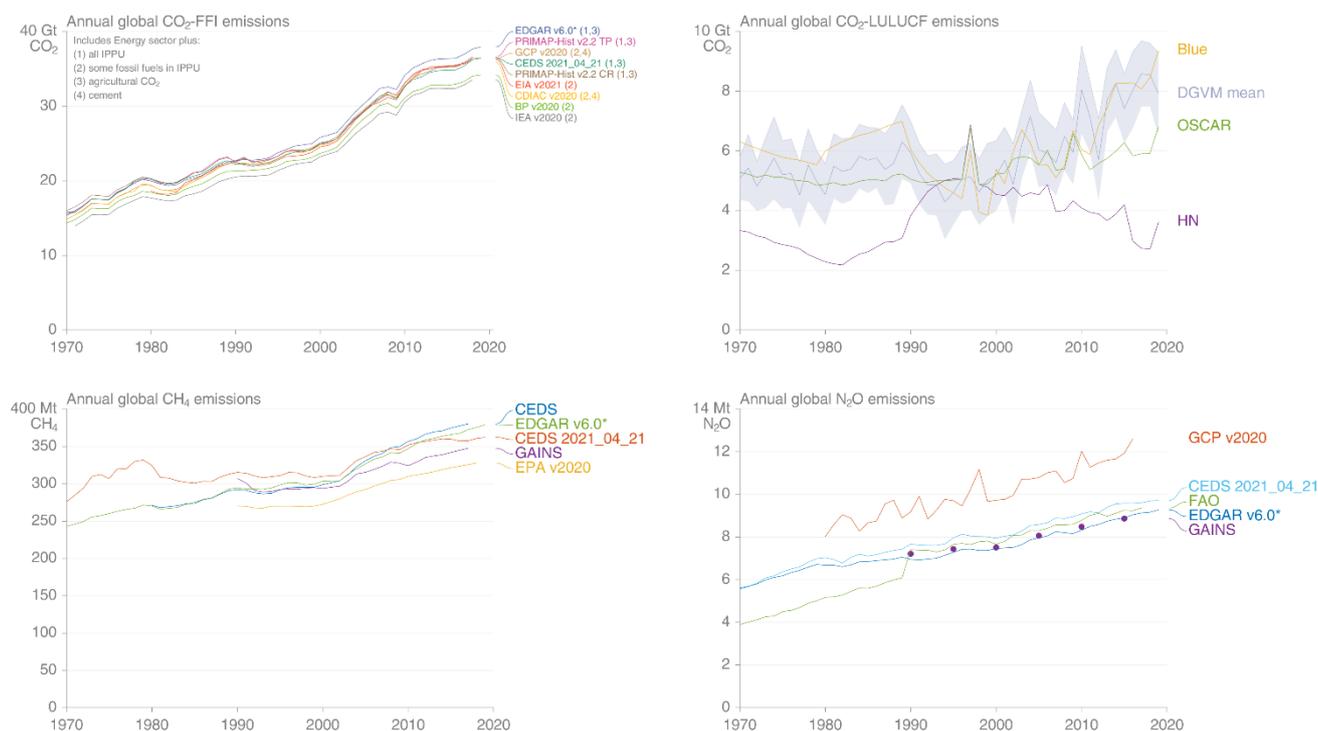



Figure 1 - Estimates of global anthropogenic greenhouse gas emissions from different data sources 1970-2019. Top-left panel: CO$_2$
FFI emissions from: EDGAR - Emissions Database for Global Atmospheric Research (this dataset) (Crippa et al., 2021); GCP – Global
Carbon Project (Friedlingstein et al., 2020); CEDS - Community Emissions Data System (Hoesly et al., 2018; O'Rourke et al., 2021); CDIAC
330   Global, Regional, and National Fossil-Fuel CO$_2$ Emissions (Gilfillan et al., 2020); PRIMAP-hist - Potsdam Real-time Integrated Model for
probabilistic Assessment of emissions Paths (Gütschow et al., 2016, 2019); EIA - Energy Information Administration International Energy
Statistics (EIA, 2021); BP - BP Statistical Review of World Energy (BP, 2020); IEA - International Energy Agency CO$_2$ Emissions from
Fuel Combustion (IEA, 2020); IPPU refers to emissions from industrial processes and product use. Top-right panel: CO$_2$-LULUCF emissions
from: BLUE – Bookkeeping of land-use emissions (Hansis et al., 2015); DGVM-mean – Multi-model mean of CO$_2$-LULUCF emissions
335   from dynamic global vegetation models (Friedlingstein et al., 2020); OSCAR – an earth system compact model (Gasser et al., 2020); HN –
Houghton and Nassikas Bookkeeping Model (Houghton and Nassikas, 2017); Bottom-left panel: Anthropogenic methane emissions from:
EDGAR (above); CEDS (above); GAINS - The Greenhouse gas – Air pollution INteractions and Synergies Model (Höglund-Isaksson,
2012); EPA-2020: Greenhouse gas emission inventory (EPA, 2021); Bottom-right panel: Anthropogenic nitrous oxide emissions from: GCP
– global nitrous oxide budget (Tian et al., 2020); CEDS (above); EDGAR (above); GAINS (above); FAO – N$_2$O emissions from the
340   FAOSTAT inventory (Tubiello et al., 2013). Differences in emissions across different versions of the EDGAR dataset are shown in the
Supplementary Material (Fig. SM-1)

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
345   emissions 1990-2019 for BLUE, H&N, OSCAR are 17, 9.6 and 19 GtCO$_2$ yr^{-1}, while gross removals are 11, 5.3, 13 GtCO$_2$ yr^{-}

[1] respectively. For 1990-2019 maximum average differences are 9.1 and 7.8 $GtCO_2$ 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

350 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).

355

Uncertainties in CO_2-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 CO_2-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.

360 Nonetheless, a CO_2-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 $GtCO_2$ yr[-1], but is still smaller than the average difference between bookkeeping models at 2.6 $GtCO_2$ 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,

365 such as crop harvesting, tillage, or grazing (all implicitly included in observation-based carbon densities of bookkeeping models) can alter CO_2 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 CO_2-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

370 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).

375 We base our uncertainty assessment on Friedlingstein et al. (2020) and take ±2.6 $GtCO_2$ yr[-1] as a best-value judgement for the ±1σ uncertainty range (thus ±5.1 $GtCO_2$ yr[-1] for ±2σ) in CO_2-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

380 ±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 CO_2-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

385 (Friedlingstein et al., 2020) and in recognition of a possible trend towards higher CO_2-LULUCF emissions estimates in more recent years.

Finally, note that attempts to constrain the estimates of CO_2-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

390 observation-driven information, remote-sensing derived estimates have limited applicability for model evaluation for the total CO_2-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

395 which fully distinguishes natural from anthropogenic disturbances.

Table 4 - Key differences between global bookkeeping estimates for CO_2-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

400 compared to the other estimates' choice.

	Bookkeeping model		
	BLUE[a]	H&N[b]	OSCAR[c]
Geographical 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[d,e]	FAO[f]	LUH2 and FAO[d,e,f]
Representation of processes (indicative effect on AFOLU CO_2 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 (↑)

Distinction rangeland vs pasture	yes (↓)	no (↑)	no (↑)
Coverage peat drainage (as in Global Carbon Budget 2020)	World (↑)[g]	South East Asia (↓)[h]	World (↑)[g]

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)

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

EDGAR mostly apply a Tier 1 approach to estimate methane emissions while GAINS uses a Tier 2 approach (Höglund-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.

435   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_4yr^{-1} before the 1990s, but these differences are smaller ranging from 1-13 MtCH_4yr^{-1} since the 2000s. The cause of these differences is a new procedure to separately
440   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
445   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
450   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
455   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.

460   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

465 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)
470 estimates, national reports and specific uncertainty assessments of EDGAR

	Estimated uncertainty in USA inventories [a]	Estimated uncertainty in EDGAR [d]	Estimated uncertainty in EDGAR [e]	Global inventories uncertainty range [b]	Saunois et al. (2020) BU uncertainty range [c]	Saunois et al. (2020) TD uncertainty range [c]
Total global anthropogenic sources (incl. Biomass burning)				-	±6%	±6%
Total global anthropogenic sources (excl. Biomass burning)		±47%	-33% to +46%	±8%		
Agriculture and Waste					±8%	±8%
Rice	na	±60%	31-38%	±22%	±20%	-
Enteric fermentation and manure management	±10 to 20% / ± 20% and up to ± 65%		±5%	±8%	-	
Landfills and Waste	±10% but likely much larger	±91%	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				-	±25%	±25%
Biomass burning				-	±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)

[*] 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 N_2O emissions

Anthropogenic N_2O 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 CO_2, 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 N_2O 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 N_2O emissions (Tian et al., 2020).

There are a variety of approaches for estimating N_2O 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), andas process-based land and ocean modelling (Tian et al., 2019; Yang et al., 2020). There are at least five relevant global N_2O emissions inventories available: EDGAR (Crippa et al., 2019, 2021; Janssens-Maenhout et al., 2019), GAINS (Höglund-Isaksson, 2012), FAO-N_2O (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-N_2O is

focused on agriculture and biomass burning and GFED on biomass burning only. As shown in Figure 1 EDGAR, GAINS,
505   CEDS and FAOSTAT emissions are consistent in magnitude and trend. Recent revisions in estimating indirect N_2O emissions
in EDGARv6 lead to an average increase of 1.5% yr^{-1} in total N_2O emissions estimates between 1999 and 2018 compared to
EDGARv5 (differences before 1999 were negligible at less than 1% yr^{-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)
510   and FAOSTAT are on average 1.5 Mt N_2O yr^{-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_2, and land cover change (Tian et al., 2020). EDGAR estimates of anthropogenic N_2O
515   emissions as used in this dataset should therefore be considered as lower bound estimates.

Anthropogenic N_2O emissions estimates are subject to considerable uncertainty – larger than those from FFI-CO_2 or CH_4
emissions. N_2O 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
520   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_2O emissions are dominated by emissions from soils, where our level of process
525   understanding is rapidly changing.

For EDGARv4.3.2 uncertainties in N_2O 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,
530   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_2O
emissions are estimated at ±50% for a 68% (1σ) 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_2O budget (Tian et al., 2020). Overall, we assess the relative uncertainty for global anthropogenic
535   N_2O 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)					
					agriculture	Fossil fuel and industry	Biomass burning	Waste and waste sector	other	Total
EDGAR	1970-2018	Global, 226 countries	4 main sectors, 24 sub-sectors	Yes	6	2.4	0.05	0.4	-	8.9
GCP	1980-2016	Global, 10 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, 172 regions	3 main sectors, 16 sub-sectors	no	6.8	1.3	-	0.7	-	8.8
FAOSTAT	1961-2017	Global, 231 countries	2 main sectors, 9 sub-sectors	Yes	8.3	-	0.9	-	-	9.2

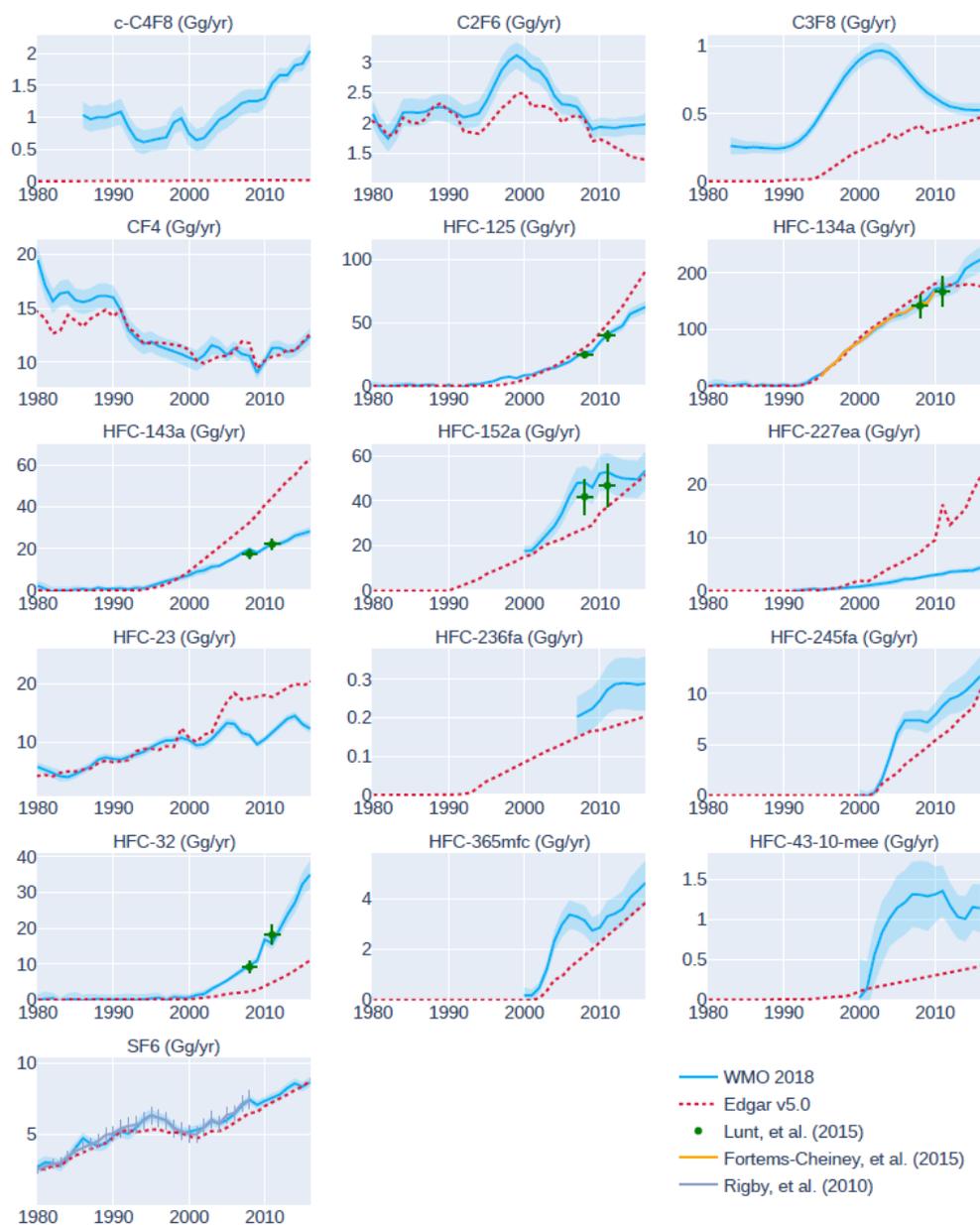
540

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;

545 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 CO_2, CH_4, N_2O, where there are also large

550 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 CF_4, C_2F_6, C_3F_8 and c-C_4F_8, and SF_6. For the higher molecular weight PFCs (C_4F_{10}, C_5F_{12}, C_6F_{14}, C_7F_{16}), 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

555   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 SF$_6$.

560   **Figure 2 - Comparison of top-down and bottom-up estimates for individual species in EDGARv5.** C$_4$F$_{10}$, C$_5$F$_{12}$, C$_6$F$_{14}$ and C$_7$F$_{16}$ 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).

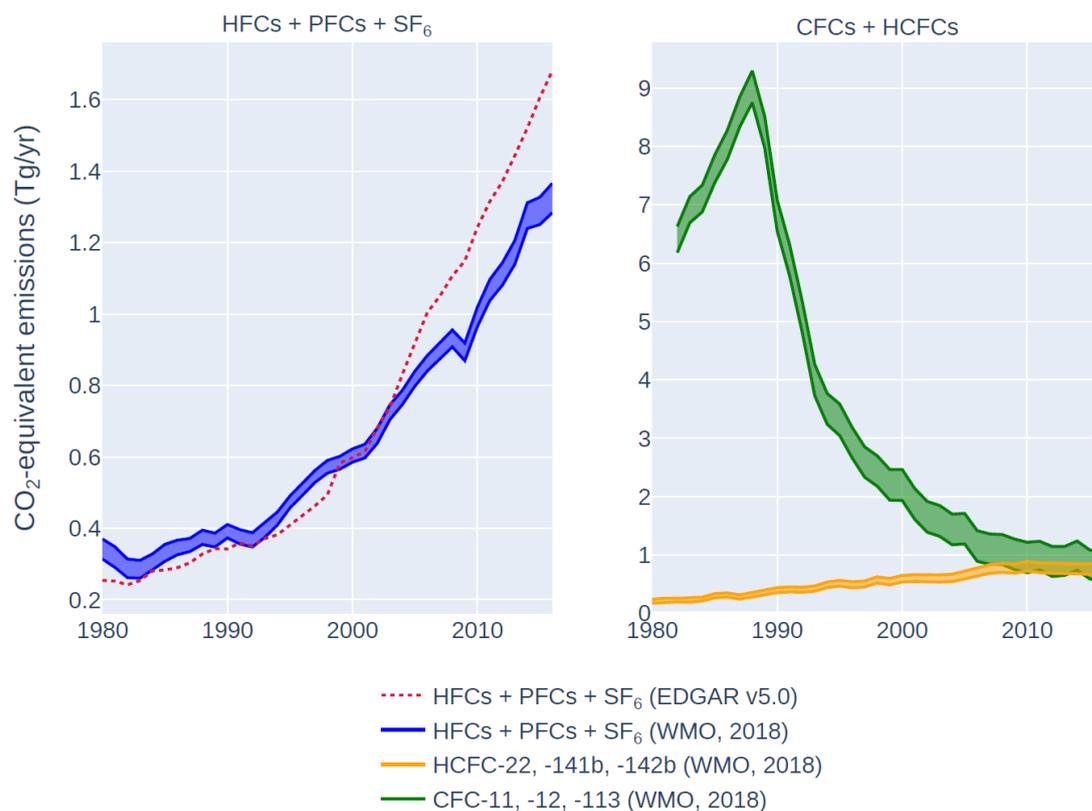



Figure 3 – Comparison between top-down estimates and bottom-up EDGARv5 inventory data on GHG emissions. Left panel: Total GWP100-weighted emissions of F-gases in EDGARv5 (red dashed line, excluding C_4F_{10}, C_5F_{12}, C_6F_{14} and C_7F_{16}) compared to top-down estimates based on AGAGE and NOAA data 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 CF_4, the median annual ratio between the top-down and bottom-up estimates is close to 1.0, whereas for c-C_4F_8 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 SF_6, 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 CF_4, these is close agreement between EDGARv4 and atmospheric observations after 1991, while for C_2F_6 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 585 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 590 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.

595 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 $GtCO_2eqyr^{-1}$ (Figure 3), comparable to that of CH_4, and substantially larger than the 2019 emissions of the gases included in EDGARv5 (1.6 $GtCO_2eq$) (Table 7). Subsequently, following the 600 controls of the Montreal Protocol, emissions of CFCs declined substantially, while those of HCFCs and HFCs rose, such that CO_2eq 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_2eq F-gas emissions in 2018.

3.6 Aggregated GHG emissions

605 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_2O (±60%) and CO_2 from LULUCF (±70%). To aggregate these and estimate uncertainties for total greenhouse gases in terms of CO_2eq 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 610 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-CO_2 gases and CO_2 are to be aggregated into CO_2eq 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 CH_4 represents as much as 86t CO_2eq 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 CO_2eq 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 CO_2 – 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 CO_2eq 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 CO_2 and non-CO_2 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
650   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-
655   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
660   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
665   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
670   ±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).

675   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.

680

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

685 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_2eq using GWP-100 (see Fig.

690 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_2eq emissions and temperature change if that is the key objective, especially if emissions are no longer rising but potentially falling, as in mitigation scenarios.

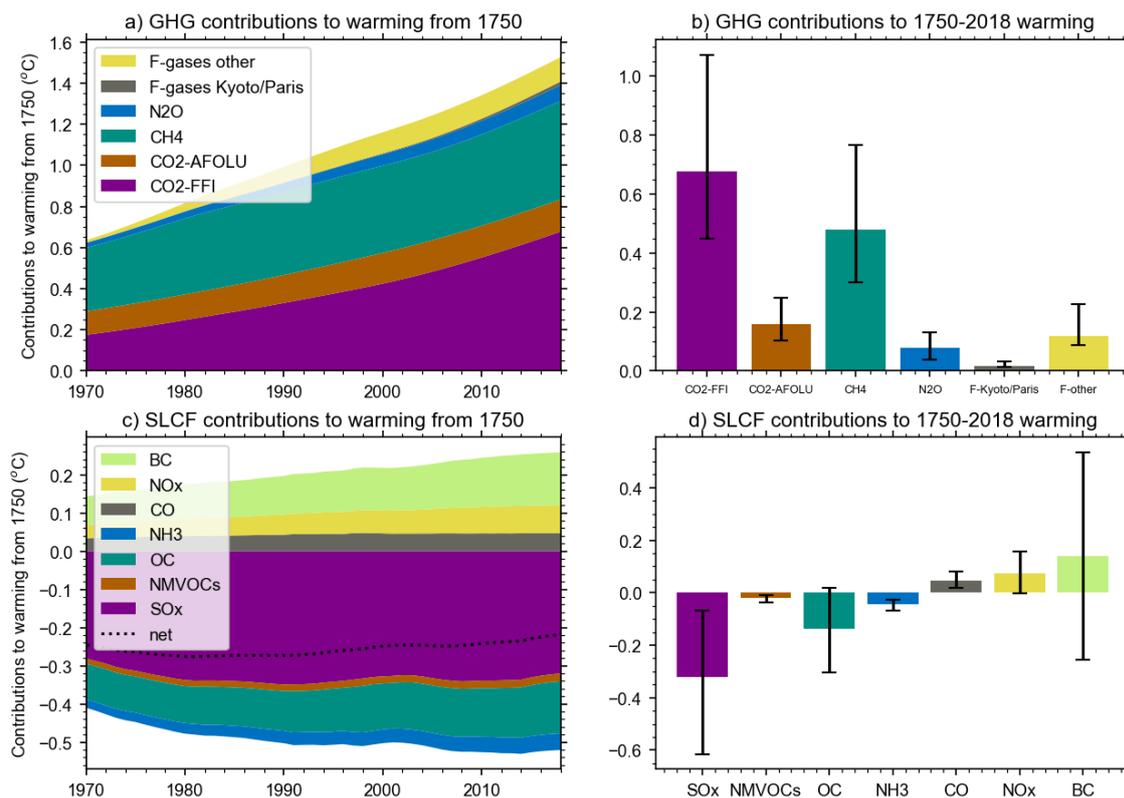



Figure 4 - Contribution of different greenhouse gases to global warming over the period 1750 to 2018. Top row: contributions from estimated with the FAIR reduced-complexity climate model. Major GHGs and aggregates of minor gases as a timeseries in a) and as a total warming bar chart with 5 % to 95 % uncertainty range added in b). Bottom row: contribution from shortshort-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 $GtCO_2eqyr^{-1}$ for the decade of the 1970s to an average of 56 ± 6.0 $GtCO_2eqyr^{-1}$ 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 CO_2-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 CO_2-FFI emission estimates increased and the share of more uncertain emission estimates such as CO_2-LULUCF or N_2O decreased.

Table 7 – Average annual anthropogenic GHG emissions and emissions growth by decade and (groups of) gases for 1970-2019: CO_2 from fossil fuel combustion and industrial processes (FFI); CO_2 from land use, land-use change and forestry (LULUCF); methane (CH_4); nitrous oxide (N_2O); fluorinated gases (F-gases). Aggregate GHG emission trends by groups of gases reported in $GtCO_2eq$ 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).

	Average annual emissions levels (GtCO₂eq yr⁻¹) and emissions growth (%)											
	CO_2 FFI		CO_2 LULUCF		CH_4		N_2O		Fluorinated gases		GHG	
	Levels	Growth	Levels	Growth	Levels	Growth	Levels	Growth	Levels	Growth	Levels	Growth
2019	38±3.0		6.6±4.6		11±3.3		2.5±1.5		1.6±0.49		59±6.6	
2010-2019	36±2.9	1.0%	5.7±4.0	1.8%	10±3.1	0.9%	2.3±1.4	1.2%	1.4±0.41	4.6%	56±6.0	1.1%
2000-2009	29±2.3	3.0%	5.3±3.7	0.4%	9.2±2.8	1.6%	2.1±1.2	1.3%	0.77±0.23	7.8%	47±5.3	2.4%
1990-1999	24±1.9	1.2%	5.0±3.5	-0.1%	8.5±2.5	0.3%	1.9±1.1	0.9%	0.39±0.12	5.2%	39±4.9	0.9%
1980-1989	21±1.6	1.6%	4.7±3.3	1.8%	7.9±2.4	1.0%	1.8±1.1	0.7%	0.26±0.078	3.8%	35±4.5	1.4%
1970-1979	18±1.4	2.8%	4.6±3.2	-1.6%	7.4±2.2	1.2%	1.6±0.98	2.0%	0.17±0.052	6.4%	32±4.3	1.7%
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 CO_2-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 $GtCO_2eqyr^{-1}$ during the 1970s (1970-1979) to 56 ± 6.0 $GtCO_2eqyr^{-1}$ during the 2010s (2010-2019), CO_2-FFI emissions doubled from 18 ± 1.4 to 36 ± 2.9 $GtCO_2eqyr^{-1}$ and F-gases grew more than sevenfold from 0.17 ± 0.052 to 1.4 ± 0.41 $GtCO_2eqyr^{-1}$ across the same time period. In fact, persistent and

730   fast growth in F-gas emissions has resulted in emissions levels that are now tracking at about 1.6 ± 0.49 $Gt\,CO_2eqyr^{-1}$ 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_2O (44%) (see Table 7).

However, there is low confidence that the reported increases in CO_2-LULUCF emissions by decade actually constitute a

735   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

740   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

745   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_2O declined consistently since the 1970, but this trend has flattened out

750   since the mid-1990s or early 2000s. Per-capita F-gas emissions show sustained and rapid growth until 2010 and have stabilized since.

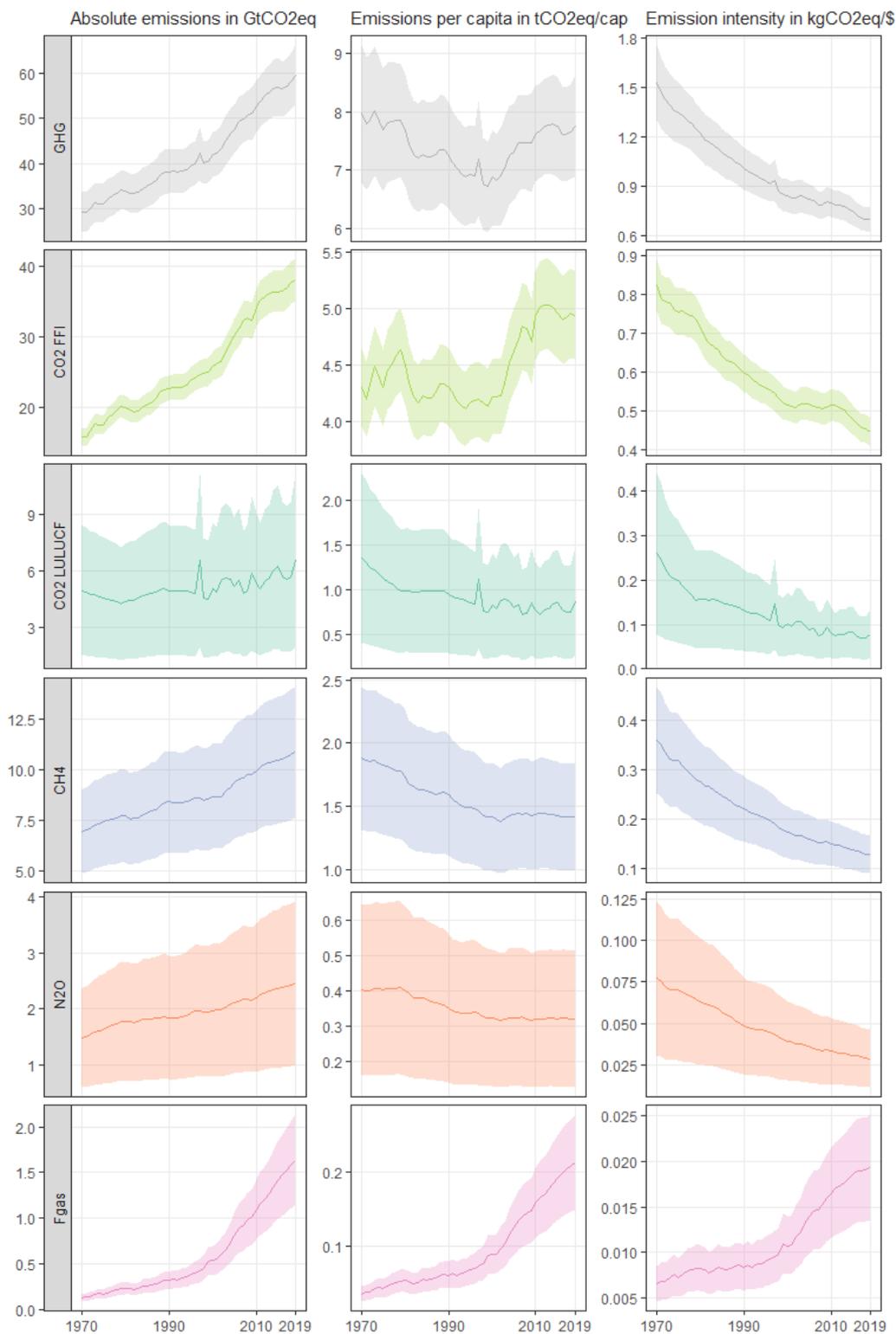



Figure 5 - Global GHG emissions trends 1970-2019 by individual (groups of) gases and in aggregate: GHGs (black); CO_2-FFI (light green); CO_2-LULUCF (dark green); methane (blue); nitrous oxide (orange); fluorinated gases (pink). Aggregate GHG emission trends by groups of gases reported in $GtCO_2eq$ converted based on global warming potentials with a 100-year time horizon (GWP-100) from the IPCC Fifth Assessment Report (Myhre et al., 2013). Coloured shadings show the associated uncertainties at a 90 % confidence interval without considering uncertainties in GDP and population data (see below). First column shows emission trends in absolute levels ($GtCO_2eq$). Second column shows per capita emissions trends (tCO_2eq/cap) using UN population data for normalization (World Bank, 2021). Third column shows emissions trends per unit of GDP ($kgCO_2eq/\$$) using GDP data in constant 2010 $ from the World Bank for normalization (World Bank, 2021).

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 $GtCO_2eqyr^{-1}$ and 3.5 to 8.1 $GtCO_2eqyr^{-1}$, respectively. In industry, average annual GHG emissions were 1.9 times larger growing from 7.3 $GtCO_2eqyr^{-1}$ in 1970-1979 to 14 $GtCO_2eqyr^{-1}$ 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 $GtCO_2eqyr^{-1}$, and 2.2 to 5.8 $GtCO_2eqyr^{-1}$. 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 $GtCO_2eqyr^{-1}$. 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 $GtCO_2eqyr^{-1}$ and 0.8 $GtCO_2eqyr^{-1}$ in 1970-1979 to 23 $GtCO_2eqyr^{-1}$ and 2.9 $GtCO_2eqyr^{-1}$ 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).

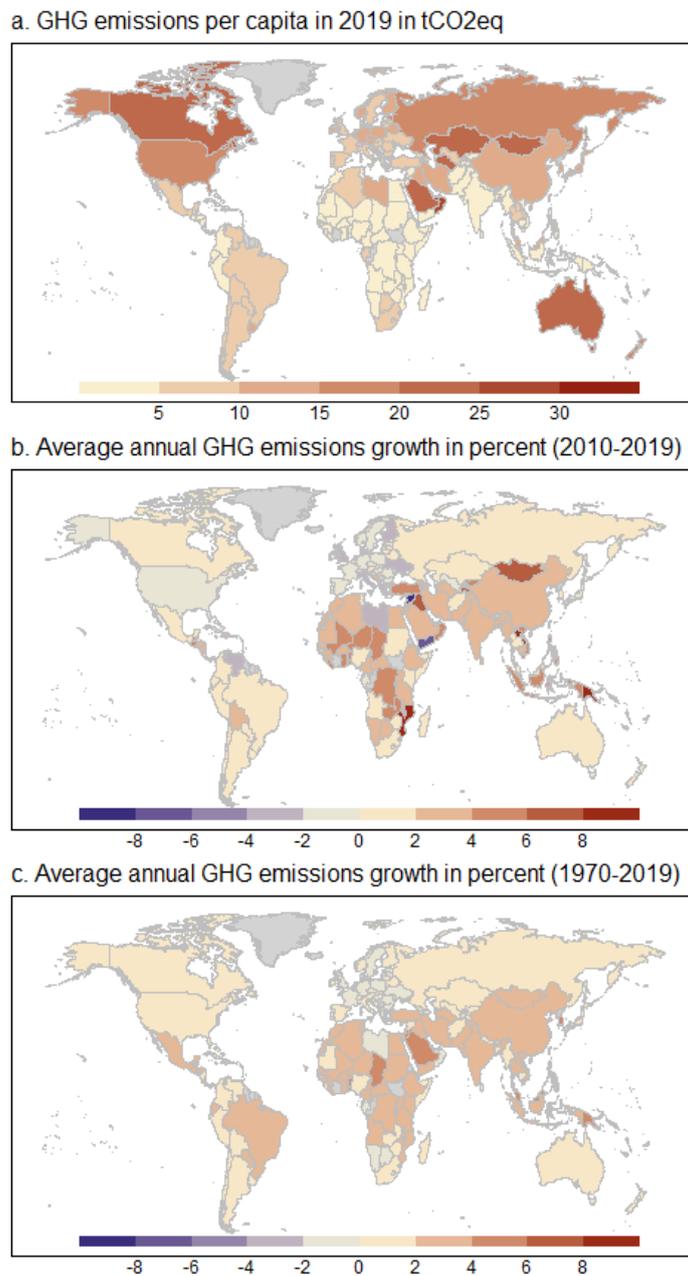



Figure 6 – Levels of and changes in GHG emissions by country. Aggregate GHG emissions are reported in GtCO₂eq converted based on
global warming potentials with a 100-year time horizon (GWP-100) from the IPCC Fifth Assessment Report (Myhre et al., 2013). Panel a
shows per capita GHG emission levels (tCO₂eq/cap) 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
795   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
800   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_2O and F-gas emissions (Sections 3.2, 3.4 and
805   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_2O emissions sit more in the
middle and at the lower-end of the scenario range – the latter driven by the lower levels of N_2O emissions in EDGAR – and
810   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_2O emissions are not reduced to zero. However, in many
815   scenarios, F-gases reach zero emissions. N_2O 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
820   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).

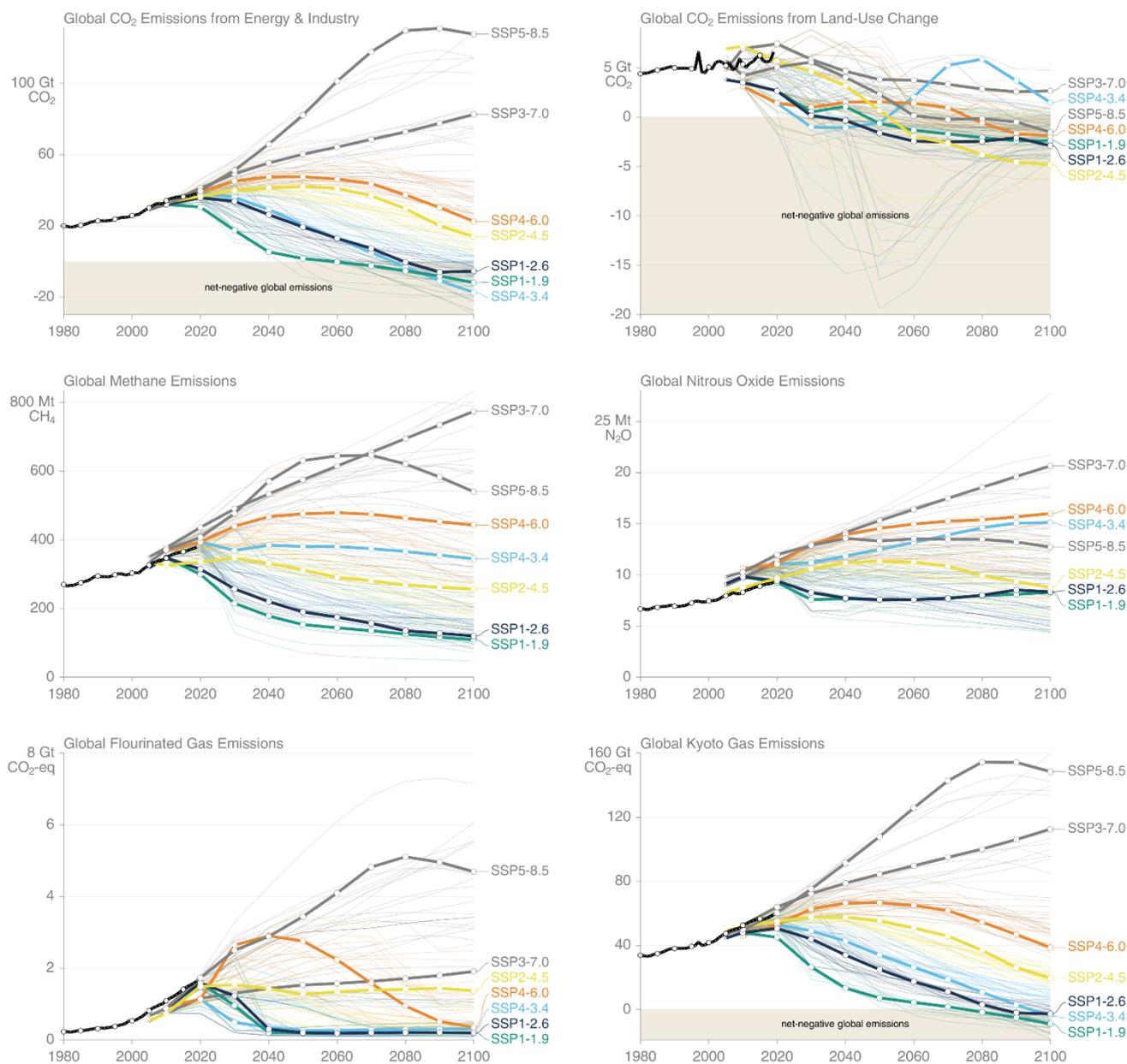



Figure 7 - Historical emissions of GHGs and future projections in socio-economic scenarios. The historical emissions are from this
825   dataset. The Shared Socioeconomic Pathways (SSPs) are from the SSP database version 2 (Riahi et al., 2017; Rogelj et al., 2018b). See also:
https://tntcat.iiasa.ac.at/SspDb/). 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

830 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$_2$eqyr^{-1} compared to 47 ± 5.4 and 39 ± 4.9 GtCO$_2$eqyr^{-1} for 2000-2009 and 1990-1999, respectively. In 2019 GHG emissions were about 6.8 ± 1.0 GtCO$_2$eqyr^{-1} or 13% higher than in 2010. F-gas and CO2-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$_2$

835 emissions from FFI contributed 3.8 ± 0.3 of the 6.8 ± 1.0 GtCO$_2$eqyr^{-1} increase in annual GHG emissions with additional contributions of 1.3 ± 0.89 GtCO$_2$eqyr^{-1} from CO$_2$-LULUCF, 0.93 ± 0.28 GtCO$_2$eqyr^{-1} from CH$_4$, 0.25 ± 0.15 GtCO$_2$eqyr^{-1} from N$_2$O and 0.55 ± 016 GtCO$_2$eqyr^{-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$_2$eqyr^{-1} from the 2000s to the 2010s has been the largest since the 1970s – and probably within all human history as

840 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$_2$eqyr^{-1}) and India (0.94 GtCO$_2$eqyr^{-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

845 (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$_2$eqyr^{-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

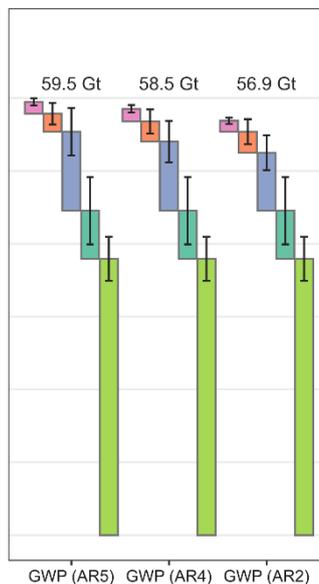
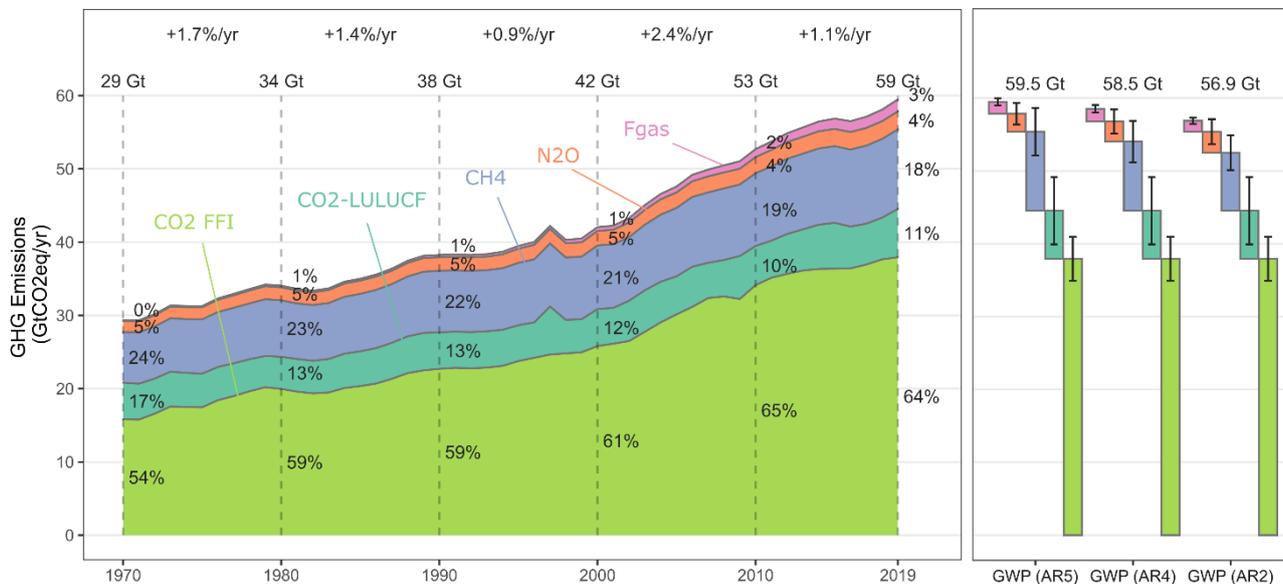
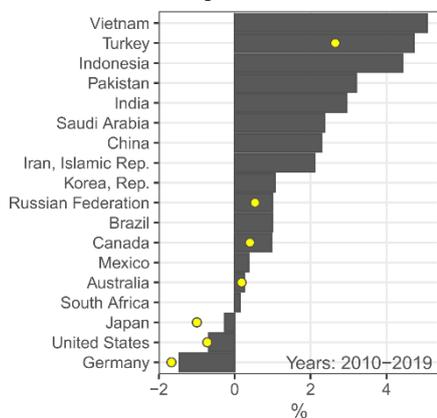
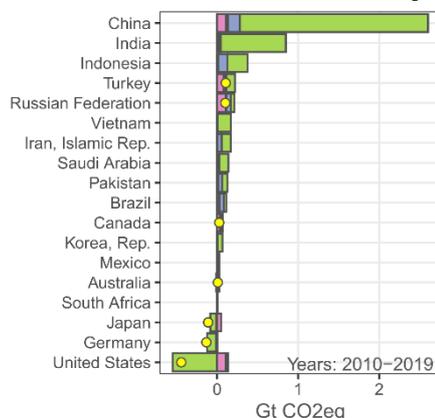
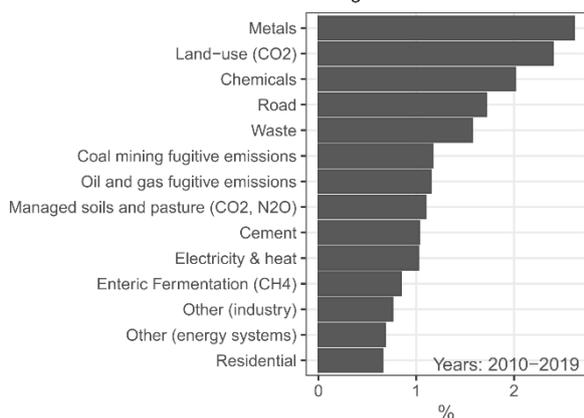
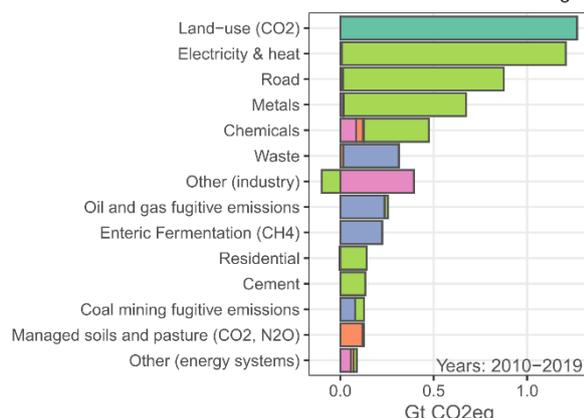
850 additional CH$_4$ (0.12 GtCO$_2$eqyr^{-1}) and F-gas (0.13 GtCO$_2$eqyr^{-1}) emissions (Figure **8**). Other countries with decreasing GHG emission levels were Germany (0.13 GtCO$_2$eqyr^{-1}) and the United Kingdom (0.14 GtCO$_2$eqyr^{-1}), where the latter shows the fastest average annual reductions 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; Strefler et al., 2018). Further information on country contributions to GHG emission changes

855 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),

860 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$_2$eqyr^{-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 $GtCO_2eqyr^{-1}$ increase in GHG emissions levels between 2010 and 2019 was from CO_2-AFOLU with about 1.3 $GtCO_2yr^{-1}$, but this estimate is much more uncertain compared to other sectors. The continued expansion of fossil-fuel based electricity production increased CO_2 emissions by about 1.2 $GtCO_2yr^{-1}$ closely followed by CO_2 emissions from road transport (0.9 $GtCO_2yr^{-1}$) and metal production (0.7 $GtCO_2yr^{-1}$) – 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 $GtCO_2yr^{-1}$). Emissions from chemical production and waste treatment are also sizable and comparatively fast growing, contributing 0.47 $GtCO_2yr^{-1}$ at 1.9% yr^{-1} and 0.31 $GtCO_2yr^{-1}$ at 1.6% yr^{-1}, respectively.

880 **Figure** 8 **- Total anthropogenic GHG emissions (Gt CO₂eq yr-1) 1970-2019: CO₂-FFI (light green); CO₂-LULUCF (dark green); methane (blue); nitrous oxide (orange); fluorinated gases (pink); all greenhouse gases (black). 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**
885 **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**

890 **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,
895 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
900 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 ($\sim0.9\pm0.6$ 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
905 GtCO₂yr^{-1} ($\Delta0.8\%$), 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
910 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

915 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 CO_2-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

920 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;
925 UNEP, 2020), but we provide some important updates. Our evidence-informed uncertainty judgements are higher for CO_2-LULUCF (±70% rather than ±50%) and CH_4 (±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
930 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
935 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 CO_2-LULUCF as well as F-gas emissions, we estimate the overall uncertainties of aggregated GHG emissions by simply
940 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).

945 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_2O 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

950   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 CO2eq 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

955   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

960   accounted for almost 75% of the emission growth since 1970 in terms of CO2eq 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

965   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

970   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.

975

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

980   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

985   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

990   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

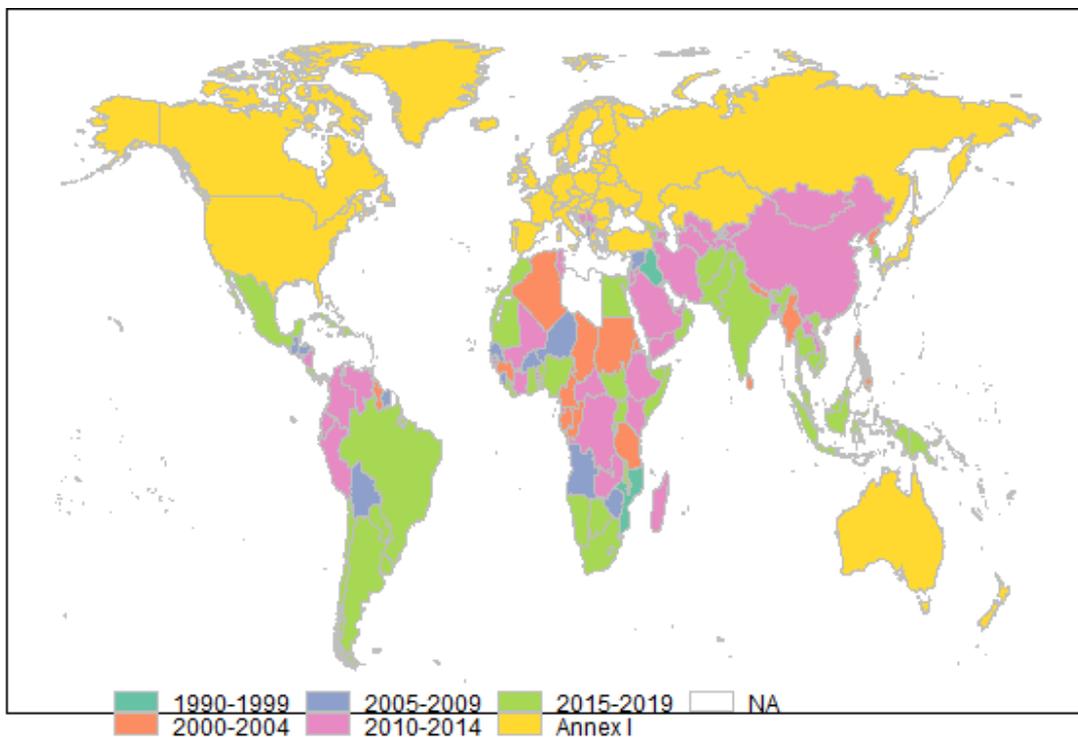
995   important and often underappreciated step.

1000

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)

1005

Data availability
The emissions dataset used for this study (Minx et al. 2021) is available at https://doi.org/10.5281/zenodo.5053056

1010 [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]

1015 **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,
1020 JGC, MC, ND, PMF, DG, JO, GPP, JP, AR, MR, MS, SJS, ES, HT).

Funding acknowledgements
The authors would like to thank Yang Ou for helpful comments on the manuscript and Eduardo Posada as well as Lucy Banisch for their help with compiling the information for Table 1 and Fig. 9, respectively. JCM and WL acknowledge funding from
1025 the German Ministry for Education and Research (grant no. 01LG1910A). RMA and GPP acknowledge funding from the European Commission Horizon 2020 projects VERIFY (grant no. 776810) and CoCO2 (grant no. 958927). PMF acknowledges funding by the European Union's Horizon 2020 Research and Innovation Programme under grant no. 820829 (CONSTRAIN). HT acknowledges funding support from the National Science Foundation (Grant #: 1903722).

1030

References

Allen, M. M. R., Shine, K. P. K., Fuglestvedt, J. J. S., Millar, R. J., Cain, M., Frame, D. J. and Macey, A. H.: A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation., Clim. Atmos.
1035   Sci., 1(16), doi:10.1038/s41612-018-0026-8, 2018.

Andres, R. J., Boden, T. A., Bréon, F. M., Ciais, P., Davis, S., Erickson, D., Gregg, J. S., Jacobson, A., Marland, G., Miller, J., Oda, T., Olivier, J. G. J., Raupach, M. R., Rayner, P. and Treanton, K.: A synthesis of carbon dioxide emissions from fossil-fuel combustion, Biogeosciences, doi:10.5194/bg-9-1845-2012, 2012.

Andres, R. J., Boden, T. A. and Higdon, D.: A new evaluation of the uncertainty associated with CDIAC estimates of fossil
1040   fuel carbon dioxide emission, Tellus, Ser. B Chem. Phys. Meteorol., doi:10.3402/tellusb.v66.23616, 2014.

Andrew, R. M.: A comparison of estimates of global carbon dioxide emissions from fossil carbon sources, Earth Syst. Sci. Data, 12, 1437–1465, 2020a.

Andrew, R. M.: Timely estimates of India's annual and monthly fossil CO2emissions, Earth Syst. Sci. Data, doi:10.5194/essd-12-2411-2020, 2020b.

1045   Arneth, A., Sitch, S., Pongratz, J., Stocker, B. D., Ciais, P., Poulter, B., Bayer, A. D., Bondeau, A., Calle, L., Chini, L. P., Gasser, T., Fader, M., Friedlingstein, P., Kato, E., Li, W., Lindeskog, M., Nabel, J. E. M. S., Pugh, T. A. M., Robertson, E., Viovy, N., Yue, C. and Zaehle, S.: Historical carbon dioxide emissions caused by land-use changes are possibly larger than assumed, Nat. Geosci., 10(2), 79–84, doi:10.1038/ngeo2882, 2017.

Baccini, A., Goetz, S. J., Walker, W. S., Laporte, N. T., Sun, M., Sulla-Menashe, D., Hackler, J., Beck, P. S. A., Dubayah, R.,
1050   Friedl, M. A., Samanta, S. and Houghton, R. A.: Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps, Nat. Clim. Chang., doi:10.1038/nclimate1354, 2012.

Baccini, A., Walker, W., Carvalho, L., Farina, M., Sulla-Menashe, D. and Houghton, R. A.: Tropical forests are a net carbon source based on aboveground measurements of gain and loss, Science (80-.)., 358(6360), 230–234, doi:10.1126/science.aam5962, 2017.

1055   Ballantyne, A. P., Andres, R., Houghton, R., Stocker, B. D., Wanninkhof, R., Anderegg, W., Cooper, L. A., DeGrandpre, M., Tans, P. P., Miller, J. B., Alden, C. and White, J. W. C.: Audit of the global carbon budget: Estimate errors and their impact on uptake uncertainty, Biogeosciences, doi:10.5194/bg-12-2565-2015, 2015.

Bastos, A., Hartung, K., Nuetzel, T., Nabel, J., Houghton, R. and Pongratz, J.: Comparison of uncertainties in land-use change fluxes from bookkeeping model parameterization, Earth Syst. Dyn., in print, 2021.

1060   Bergamaschi, P., Houweling, S., Segers, A., Krol, M., Frankenberg, C., Scheepmaker, R. A., Dlugokencky, E., Wofsy, S. C., Kort, E. A., Sweeney, C., Schuck, T., Brenninkmeijer, C., Chen, H., Beck, V. and Gerbig, C.: Atmospheric CH4 in the first decade of the 21st century: Inverse modeling analysis using SCIAMACHY satellite retrievals and NOAA surface measurements, J. Geophys. Res. Atmos., 118(13), 7350–7369, doi:https://doi.org/10.1002/jgrd.50480, 2013.

Blanco G., Gerlagh, R., Suh, S., Barrett, J., Coninck, H. C. de, Morejon, C. F. D., Mathur, R., Nakicenovic, N., Ahenkora, A.

1065   O., Pan, J., Pathak, H., Rice, J., Richels, R., Smith, S. J., Stern, D. I., Toth, F. L. and Zhou, P.: Chapter 5: Drivers, Trends and Mitigation, in Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change., 2014.

BP: Statistical Review of World Energy 2019, London, UK., 2019.

BP: Statistical Review of World Energy, London, UK. [online] Available from:
1070   https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html, 2020.

Buitenhuis, E. T., Suntharalingam, P. and Le Quéré, C.: Constraints on global oceanic emissions of N2O from observations and models, Biogeosciences, doi:10.5194/bg-15-2161-2018, 2018.

Cain, M., Lynch, J., Allen, M. M. R., Fuglestvedt, J. S., Frame, D. J. and Macey, A. H.: Improved calculation of warming-equivalent emissions for short-lived climate pollutants, Clim. Atmos. Sci., 2(1), doi:10.1038/s41612-019-0086-4, 2019.

1075   Chang, N. and Lahr, M. L.: Changes in China's production-source CO2 emissions: insights from structural decomposition analysis and linkage analysis, Econ. Syst. Res. Cited By - 23, 28, 224-242 Funding details-National Natural Scienc, doi:10.1080/09535314.2016.1172476 Correspondence Address - grace_cn@mail.shufe.edu.cn, 2016.

Chini, L., Hurtt, G., Sahajpal, R., Frolking, S., Klein Goldewijk, K., Sitch, S., Ganzenmüller, R., Ma, L., Ott, L., Pongratz, J. and Poulter, B.: Land-Use Harmonization Datasets for Annual Global Carbon Budgets, Earth Syst. Sci. Data, submitted, 2020.

1080   Ciais, P., Sabine, C. and Bala, G.: Chapter 6: Carbon and other biogeochemical cycles, Clim. Chang. 2013 Phys. Sci. Basis, 2014.

Ciais, P., Yao, Y., Gasser, T., Baccini, A., Wang, Y., Lauerwald, R., Peng, S., Bastos, A., Li, W., Raymond, P. A., Canadell, J. G., Peters, G. P., Andres, R. J., Chang, J., Yue, C., Dolman, A. J., Haverd, V., Hartmann, J., Laruelle, G., Konings, A. G., King, A. W., Liu, Y., Luyssaert, S., Maignan, F., Patra, P. K., Peregon, A., Regnier, P., Pongratz, J., Poulter, B., Shvidenko, 1085   A., Valentini, R., Wang, R., Broquet, G., Yin, Y., Zscheischler, J., Guenet, B., Goll, D. S., Ballantyne, A.-P., Yang, H., Qiu, C. and Zhu, D.: Empirical estimates of regional carbon budgets imply reduced global soil heterotrophic respiration, Natl. Sci. Rev., 8(2), doi:10.1093/nsr/nwaa145, 2021.

Collins, W. J., Frame, D. J., Fuglestvedt, J. and Shine, K. P.: Stable climate metrics for emissions of short and long-lived species – combining steps and pulses, Environ. Res. Lett., doi:10.1088/1748-9326/ab6039, 2019.

1090   Conchedda, G. and Tubiello, F. N.: Drainage of organic soils and GHG emissions: Validation with country data, Earth Syst. Sci. Data, 12, 3113–3137, doi:10.5194/essd-2020-202, 2020.

Crippa, M., Oreggioni, G., Guizzardi, D., Muntean, M., Schaaf, E., Lo Vullo, E., Solazzo, E., Monforti-Ferrario, F., Olivier, J. G. J. and Vignati, E.: Fossil CO2 and GHG emissions of all world countries - 2019 Report, Luxembourg., 2019.

Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Solazzo, E., Monforti-Ferrario, F., Olivier, J. G. J. and Vignati, E.: Fossil 1095   CO2 emissions of all world countries - 2020 Report, Luxembourg., 2020.

Crippa, M., Guizzardi, D., Schaaf, E., Solazzo, E., Muntean, M., Monforti-Ferrario, F., Olivier, J. G. J. and Vignati, E.: Fossil CO2 and GHG emissions of all world countries - 2021 Report., 2021.

Crutzen, P. J., Mosier, A. R., Smith, K. A. and Winiwarter, W.: N2O release from agro-biofuel production negates global

warming reduction by replacing fossil fuels, Atmos. Chem. Phys., doi:10.5194/acp-8-389-2008, 2008.

1100 Darmenov, A. and da Silva, A. M.: The Quick Fire Emissions Dataset (QFED) - Documentation of versions 2.1, 2.2 and 2.4., NASA Tech. Rep. Ser. Glob. Model. Data Assim., 2013.

EIA: International Energy Statistics, [online] Available from: https://www.eia.gov/beta/international/data/browser/ (Accessed 1 July 2021), 2021.

Elberling, B., Christiansen, H. H. and Hansen, B. U.: High nitrous oxide production from thawing permafrost, Nat. Geosci.,

1105 doi:10.1038/ngeo803, 2010.

Engel, A. and Rigby, M.: Chapter 1: Update on Ozone Depleting Substances (ODSs) and Other Gases of Interest to the Montreal Protocol, in Scientific Assessment of Ozone Depletion: 2018, World Meterological Organization, Geneva, Switzerland., 2018.

EPA: Global Anthropogenic Non-CO 2 Greenhouse Gas Emissions : 1990 - 2030, Off. Atmos. Programs Clim. Chang. Div.

1110 U.S. Environ. Prot. Agency, 2011.

EPA: Global Non-CO2Greenhouse Gas Emission Projections & Mitigation: 2015-2015, Washington D.C., USA. [online] Available from: https://www.epa.gov/sites/production/files/2019-09/documents/epa_non-co2_greenhouse_gases_rpt-epa430r19010.pdf, 2021.

Etiope, G., Ciotoli, G., Schwietzke, S. and Schoell, M.: Gridded maps of geological methane emissions and their isotopic

1115 signature, Earth Syst. Sci. Data, doi:10.5194/essd-11-1-2019, 2019.

Etminan, M., Myhre, G., Highwood, E. J. and Shine, K. P.: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing, Geophys. Res. Lett., 43(24), 12,612-614,623, doi:10.1002/2016GL071930, 2016.

FAO and GRA: Livestock Activity Data Guidance (L-ADG): Methods and guidance on compilation of activity data for Tier

1120 2 livestock GHG inventories., 2020.

Federici, S., Tubiello, F. N., Salvatore, M., Jacobs, H. and Schmidhuber, J.: New estimates of CO2 forest emissions and removals: 1990-2015, For. Ecol. Manage., 352, 89–98, doi:10.1016/j.foreco.2015.04.022, 2015.

Fortems-Cheiney, A., Saunois, M., Pison, I., Chevallier, F., Bousquet, P., Cressot, C., Montzka, S. A., Fraser, P. J., Vollmer, M. K., Simmonds, P. G., Young, D., O'Doherty, S., Weiss, R. F., Artuso, F., Barletta, B., Blake, D. R., Li, S., Lunder, C.,

1125 Miller, B. R., Park, S., Prinn, R., Saito, T., Steele, L. P. and Yokouchi, Y.: Increase in HFC-134a emissions in response to the success of the Montreal Protocol, J. Geophys. Res. Atmos., 120(22), 11,711-728,742, doi:https://doi.org/10.1002/2015JD023741, 2015.

Friedlingstein, P., Meinshausen, M., Arora, V. K., Jones, C. D., Anav, A., Liddicoat, S. K. and Knutti, R.: Uncertainties in CMIP5 Climate Projections due to Carbon Cycle Feedbacks, J. Clim., 27(2), 511–526, doi:10.1175/JCLI-D-12-00579.1, 2013.

1130 Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Hauck, J., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Le Quéré, C., Bakker, D. C. E., Canadell, J. G., Ciais, P., Jackson, R. B., Anthoni, P., Barbero, L., Bastos, A., Bastrikov, V., Becker, M., Bopp, L., Buitenhuis, E., Chandra, N., Chevallier, F., Chini, L. P., Currie, K. I., Feely, R. A., Gehlen, M., Gilfillan,

D., Gkritzalis, T., Goll, D. S., Gruber, N., Gutekunst, S., Harris, I., Haverd, V., Houghton, R. A., Hurtt, G., Ilyina, T., Jain, A. K., Joetzjer, E., Kaplan, J. O., Kato, E., Klein Goldewijk, K., Korsbakken, J. I., Landschützer, P., Lauvset, S. K., Lefèvre, N.,

1135 Lenton, A., Lienert, S., Lombardozzi, D., Marland, G., McGuire, P. C., Melton, J. R., Metzl, N., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S.-I., Neill, C., Omar, A. M., Ono, T., Peregon, A., Pierrot, D., Poulter, B., Rehder, G., Resplandy, L., Robertson, E., Rödenbeck, C., Séférian, R., Schwinger, J., Smith, N., Tans, P. P., Tian, H., Tilbrook, B., Tubiello, F. N., van der Werf, G. R., Wiltshire, A. J. and Zaehle, S.: Global Carbon Budget 2019, Earth Syst. Sci. Data, 11(4), 1783–1838, doi:10.5194/essd-11-1783-2019, 2019.

1140 Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Le Quéré, C., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S., Aragão, L. E. O. C., Arneth, A., Arora, V., Bates, N. R., Becker, M., Benoit-Cattin, A., Bittig, H. C., Bopp, L., Bultan, S., Chandra, N., Chevallier, F., Chini, L. P., Evans, W., Florentie, L., Forster, P. M., Gasser, T., Gehlen, M., Gilfillan, D., Gkritzalis, T., Gregor, L., Gruber, N., Harris, I., Hartung, K., Haverd, V., Houghton, R. A., Ilyina, T., Jain, A. K., Joetzjer, E., Kadono, K., Kato, E., Kitidis, V., Korsbakken, J. I.,

1145 Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Liu, Z., Lombardozzi, D., Marland, G., Metzl, N., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S.-I., Niwa, Y., O'Brien, K., Ono, T., Palmer, P. I., Pierrot, D., Poulter, B., Resplandy, L., Robertson, E., Rödenbeck, C., Schwinger, J., Séférian, R., Skjelvan, I., Smith, A. J. P., Sutton, A. J., Tanhua, T., Tans, P. P., Tian, H., Tilbrook, B., van der Werf, G., Vuichard, N., Walker, A. P., Wanninkhof, R., Watson, A. J., Willis, D., Wiltshire, A. J., Yuan, W., Yue, X. and Zaehle, S.: Global Carbon Budget 2020, Earth Syst. Sci. Data, 12(4), 3269–3340, doi:10.5194/essd-12-3269-

1150 2020, 2020.

Galloway, J., Dentener, F., Burke, M., Dumont, E. L., Bouwman, A., Kohn, R., Mooney, H., Seitzinger, S. and Kroeze, C.: The impact of animal production systems on the nitrogen cycle, Livest. a Chang. Landscape. Drivers, Consequences Responses, 1, 2010.

Gasser, T., Peters, G. P., Fuglestvedt, J. S., Collins, W. J., Shindell, D. T. and Ciais, P.: Accounting for the climate-carbon

1155 feedback in emission metrics, Earth Syst. Dynam. Discuss., 2016, 1–29, doi:10.5194/esd-2016-55, 2016.

Gasser, T., Crepin, L., Quilcaille, Y., Houghton, R. A., Ciais, P. and Obersteiner, M.: Historical CO2 emissions from land use and land cover change and their uncertainty, Biogeosciences, 17(15), 4075–4101, doi:10.5194/bg-17-4075-2020, 2020.

Gidden, M. J., Riahi, K., Smith, S. J., Fujimori, S., Luderer, G., Kriegler, E., van Vuuren, D. P., van den Berg, M., Feng, L., Klein, D., Calvin, K., Doelman, J. C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlik, P., Hilaire, J., Hoesly, R.,

1160 Horing, J., Popp, A., Stehfest, E. and Takahashi, K.: Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century, Geosci. Model Dev., 12(4), 1443–1475, doi:10.5194/gmd-12-1443-2019, 2019.

Giglio, L., Randerson, J. T. and Van Der Werf, G. R.: Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4), J. Geophys. Res. Biogeosciences, doi:10.1002/jgrg.20042, 2013.

1165 Gilfillan, D., Marland, G., Boden, T. and Andres, R.: Global, Regional, and National Fossil-Fuel CO2 Emissions: 1751-2017, , doi:10.5281/ZENODO.4281271, 2020.

Grassi, G., House, J., Kurz, W. A., Cescatti, A., Houghton, R. A., Peters, G. P., Sanz, M. J., Viñas, R. A., Alkama, R., Arneth, A., Bondeau, A., Dentener, F., Fader, M., Federici, S., Friedlingstein, P., Jain, A. K., Kato, E., Koven, C. D., Lee, D., Nabel, J. E. M. S., Nassikas, A. A., Perugini, L., Rossi, S., Sitch, S., Viovy, N., Wiltshire, A. and Zaehle, S.: Reconciling global-

1170   model estimates and country reporting of anthropogenic forest CO2 sinks, Nat. Clim. Chang., doi:10.1038/s41558-018-0283-x, 2018.

Gregg, J. S., Andres, R. J. and Marland, G.: China: Emissions pattern of the world leader in CO2 emissions from fossil fuel consumption and cement production, Geophys. Res. Lett., doi:10.1029/2007GL032887, 2008.

Guan, D., Liu, Z., Geng, Y., Lindner, S. and Hubacek, K.: The gigatonne gap in China's carbon dioxide inventories, Nat. Clim.

1175   Chang., doi:10.1038/nclimate1560, 2012.

Guo, R., Wang, J., Bing, L., Tong, D., Ciais, P., Davis, S. J., Andrew, R. M., Xi, F. and Liu, Z.: Global CO2 uptake by cement from 1930 to 2019, Earth Syst. Sci. Data, 13(4), 1791–1805, doi:10.5194/essd-13-1791-2021, 2021.

Gütschow, J., Jeffery, M. L., Gieseke, R., Gebel, R., Stevens, D., Krapp, M. and Rocha, M.: The PRIMAP-hist national historical emissions time series, Earth Syst. Sci. Data, doi:10.5194/essd-8-571-2016, 2016.

1180   Gütschow, J., Jeffery, L. M. and Gieseke, R.: The PRIMAP-hist national historical emissions time series (1850-2016). V. 2.0, , doi:http://doi.org/10.5880/PIK.2019.001, 2019.

Gütschow, J., Jeffery, M. L. and Günther, A.: PRIMAP-crf: UNFCCC CRF data in IPCC categories (PRIMAP-crf-2021-v1), , doi:10.5281/ZENODO.4723476, 2021.

Hansen, M. C., Potapov, P. V, Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., Thau, D., Stehman, S. V, Goetz,

1185   S. J., Loveland, T. R., Kommareddy, A., Egorov, A., Chini, L., Justice, C. O. and Townshend, J. R. G.: High-Resolution Global Maps of 21st-Century Forest Cover Change, Science (80-.)., 342(6160), 850 LP – 853, doi:10.1126/science.1244693, 2013.

Hansis, E., Davis, S. J. and Pongratz, J.: Relevance of methodological choices for accounting of land use change carbon fluxes, Global Biogeochem. Cycles, doi:10.1002/2014GB004997, 2015.

Hartung, K., Bastos, A., Chini, L., Ganzenmüller, R., Havermann, F., Hurtt, G. C., Loughran, T., Nabel, J. E. M. S., Nützel,

1190   T., Obermeier, W. A. and Pongratz, J.: Net land-use change carbon flux estimates and sensitivities – An assessment with a bookkeeping model based on CMIP6 forcing, Earth Syst. Dynam. Discuss., 2021, 1–34, doi:10.5194/esd-2020-94, 2021.

Hausfather, Z. and Peters, G. P.: Emissions – the 'business as usual' story is misleading, Nature, doi:10.1038/d41586-020-00177-3, 2020a.

Hausfather, Z. and Peters, G. P.: RCP8.5 is a problematic scenario for near-term emissions, Proc. Natl. Acad. Sci., 117(45),

1195   27791 LP – 27792, doi:10.1073/pnas.2017124117, 2020b.

Hilaire, J., Minx, J. C., Callaghan, M. W., Edmonds, J., Luderer, G., Nemet, G. F., Rogelj, J. and del Mar Zamora, M.: Negative emissions and international climate goals—learning from and about mitigation scenarios, Clim. Change, doi:10.1007/s10584-019-02516-4, 2019.

Hoesly, R. M. and Smith, S. J.: Informing energy consumption uncertainty: An analysis of energy data revisions, Environ.

1200   Res. Lett., doi:10.1088/1748-9326/aaebc3, 2018.

Hoesly, R. M., Smith, S. J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J. J., Vu, L., Andres, R. J., Bolt, R. M., Bond, T. C., Dawidowski, L., Kholod, N., Kurokawa, J. I., Li, M., Liu, L., Lu, Z., Moura, M. C. P., O'Rourke, P. R. and Zhang, Q.: Historical (1750-2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS), Geosci. Model Dev., doi:10.5194/gmd-11-369-2018, 2018.

1205 Höglund-Isaksson, L.: Global anthropogenic methane emissions 2005-2030: Technical mitigation potentials and costs, Atmos. Chem. Phys., doi:10.5194/acp-12-9079-2012, 2012.

Höglund-Isaksson, L., Gómez-Sanabria, A., Klimont, Z., Rafaj, P. and Schöpp, W.: Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe –results from the GAINS model, Environ. Res. Commun., 2(2), 25004, doi:10.1088/2515-7620/ab7457, 2020.

1210 Hooijer, A., Page, S., Canadell, J. G., Silvius, M., Kwadijk, J., Wösten, H. and Jauhiainen, J.: Current and future CO_2 emissions from drained peatlands in Southeast Asia, Biogeosciences, 7(5), 1505–1514, doi:10.5194/bg-7-1505-2010, 2010.

Houghton, R. A.: Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000, Tellus, Ser. B Chem. Phys. Meteorol., doi:10.1034/j.1600-0889.2003.01450.x, 2003.

Houghton, R. A. and Nassikas, A. A.: Global and regional fluxes of carbon from land use and land cover change 1850–2015,
1215 Global Biogeochem. Cycles, doi:10.1002/2016GB005546, 2017.

Houghton, R. A., House, J. I., Pongratz, J., Van Der Werf, G. R., Defries, R. S., Hansen, M. C., Le Quéré, C. and Ramankutty, N.: Carbon emissions from land use and land-cover change, Biogeosciences, doi:10.5194/bg-9-5125-2012, 2012.

Houweling, S., Bergamaschi, P., Chevallier, F., Heimann, M., Kaminski, T., Krol, M., Michalak, A. M. and Patra, P.: Global inverse modeling of CH4 sources and sinks: An overview of methods, Atmos. Chem. Phys., doi:10.5194/acp-17-235-2017,
1220 2017.

Hu, Z., Lee, J. W., Chandran, K., Kim, S. and Khanal, S. K.: Nitrous oxide (N 2O) emission from aquaculture: A review, Environ. Sci. Technol., doi:10.1021/es300110x, 2012.

Hurtt, G. C., Chini, L., Sahajpal, R., Frolking, S., Bodirsky, B. L., Calvin, K., Doelman, J. C., Fisk, J., Fujimori, S., Goldewijk, K. K., Hasegawa, T., Havlik, P., Heinimann, A., Humpenöder, F., Jungclaus, J., Kaplan, J. O., Kennedy, J., Krisztin, T.,
1225 Lawrence, D., Lawrence, P., Ma, L., Mertz, O., Pongratz, J., Popp, A., Poulter, B., Riahi, K., Shevliakova, E., Stehfest, E., Thornton, P., Tubiello, F. N., van Vuuren, D. P. and Zhang, X.: Harmonization of global land use change and management for the period 850-2100 (LUH2) for CMIP6., 2020.

IEA: CO2 Emissions from Fossil Fuel Combustion 2020, Paris, France. [online] Available from: https://www.iea.org/data-and-statistics/data-product/co2-emissions-from-fuel-combustion, 2020.

1230 IPCC: Guidelines for National Greenhouse Gas Inventories., Agric. For. other L. use, doi:10.1016/j.phrs.2011.03.002, 2006.

IPCC: Climate Change 2014: Synthesis Report., 2014.

IPCC: Refinement to the 2006 IPCC Guidelines for National Greenhouse gas Inventories, Geneva, Switzerland., 2019.

Ivy, D. J., Rigby, M., Baasandorj, M., Burkholder, J. B. and Prinn, R. G.: Global emission estimates and radiative impact of C_4F_{10}, C_5F_{12}, C_6F_{14}, C_7F_{16} and C_8F_{18}, Atmos. Chem. Phys., 12(16), 7635–7645, doi:10.5194/acp-12-7635-2012, 2012.

1235   Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., Bergamaschi, P., Pagliari, V., Olivier, J., Peters, J., van Aardenne, J., Monni, S., Doering, U., Petrescu, R., Solazzo, E. and Oreggioni, G.: EDGAR v4.3.2 Global Atlas of the three major Greenhouse Gas Emissions for the period 1970–2012, Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2018-164, 2019.

Kaiser, J. W., Heil, A., Andreae, M. O., Benedetti, A., Chubarova, N., Jones, L., Morcrette, J. J., Razinger, M., Schultz, M.
1240   G., Suttie, M. and Van Der Werf, G. R.: Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power, Biogeosciences, doi:10.5194/bg-9-527-2012, 2012.

Kirschke, S., Bousquet, P., Ciais, P., Saunois, M., Canadell, J. G., Dlugokencky, E. J., Bergamaschi, P., Bergmann, D., Blake, D. R., Bruhwiler, L., Cameron-Smith, P., Castaldi, S., Chevallier, F., Feng, L., Fraser, A., Heimann, M., Hodson, E. L., Houweling, S., Josse, B., Fraser, P. J., Krummel, P. B., Lamarque, J. F., Langenfelds, R. L., Le Quéré, C., Naik, V., O'doherty,
1245   S., Palmer, P. I., Pison, I., Plummer, D., Poulter, B., Prinn, R. G., Rigby, M., Ringeval, B., Santini, M., Schmidt, M., Shindell, D. T., Simpson, I. J., Spahni, R., Steele, L. P., Strode, S. A., Sudo, K., Szopa, S., Van Der Werf, G. R., Voulgarakis, A., Van Weele, M., Weiss, R. F., Williams, J. E. and Zeng, G.: Three decades of global methane sources and sinks, Nat. Geosci., 6(10), 813–823, doi:10.1038/ngeo1955, 2013.

Klein Goldewijk, K., Beusen, A., Doelman, J. and Stehfest, E.: Anthropogenic land use estimates for the Holocene – HYDE
1250   3.2, Earth Syst. Sci. Data, 9(2), 927–953, doi:10.5194/essd-9-927-2017, 2017.

Korsbakken, J. I., Peters, G. P. and Andrew, R. M.: Uncertainties around reductions in China's coal use and CO 2 emissions, Nat. Clim. Chang., doi:10.1038/nclimate2963, 2016.

Kroeze, C., Mosier, A. and Bouwman, L.: Closing the global N2O budget: A retrospective analysis 1500-1994, Global Biogeochem. Cycles, doi:10.1029/1998GB900020, 1999.

1255   Lamb, W. F., Wiedmann, T., Pongratz, J., Andrew, R., Crippa, M., Olivier, J. G. J., Wiedenhofer, D., Mattioli, G., Khourdajie, A. Al, House, J., Pachauri, S., Figueroa, M., Saheb, Y., Slade, R., Hubacek, K., Sun, L., Ribeiro, S. K., Khennas, S., Can, S. de la R. du, Chapungu, L., Davis, S. J., Bashmakov, I., Dai, H., Dhakal, S., Tan, X., Geng, Y., Gu, B. and Minx, J. C.: A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018, Environ. Res. Lett. [online] Available from: http://iopscience.iop.org/article/10.1088/1748-9326/abee4e, 2021a.

1260   Lamb, W. F., Diluiso, F., Grubb, M. and Minx., J. C.: Progress in national greenhouse gas emissions reductions, Clim. Policy, submitted, 2021b.

Li, W., Ciais, P., Peng, S., Yue, C., Wang, Y., Thurner, M., Saatchi, S. S., Arneth, A., Avitabile, V., Carvalhais, N., Harper, A. B., Kato, E., Koven, C., Liu, Y. Y., Nabel, J. E. M. S., Pan, Y., Pongratz, J., Poulter, B., Pugh, T. A. M., Santoro, M., Sitch, S., Stocker, B. D., Viovy, N., Wiltshire, A., Yousefpour, R. and Zaehle, S.: Land-use and land-cover change carbon emissions
1265   between 1901 and 2012 constrained by biomass observations, Biogeosciences, doi:10.5194/bg-14-5053-2017, 2017.

Li, W., MacBean, N., Ciais, P., Defourny, P., Lamarche, C., Bontemps, S., Houghton, R. A. and Peng, S.: Gross and net land cover changes in the main plant functional types derived from the annual ESA CCI land cover maps (1992–2015), Earth Syst. Sci. Data, 10(1), 219–234, doi:10.5194/essd-10-219-2018, 2018.

Locatelli, R., Bousquet, P., Saunois, M., Chevallier, F. and Cressot, C.: Sensitivity of the recent methane budget to LMDz sub-grid-scale physical parameterizations, Atmos. Chem. Phys., 15(17), 9765–9780, doi:10.5194/acp-15-9765-2015, 2015.

Louise Jeffery, M., Gütschow, J., Gieseke, R. and Gebel, R.: PRIMAP-crf: UNFCCC CRF data in IPCC 2006 categories, Earth Syst. Sci. Data, doi:10.5194/essd-10-1427-2018, 2018.

Lunt, M. F., Rigby, M., Ganesan, A. L., Manning, A. J., Prinn, R. G., O'Doherty, S., Mühle, J., Harth, C. M., Salameh, P. K., Arnold, T., Weiss, R. F., Saito, T., Yokouchi, Y., Krummel, P. B., Steele, L. P., Fraser, P. J., Li, S., Park, S., Reimann, S., Vollmer, M. K., Lunder, C., Hermansen, O., Schmidbauer, N., Maione, M., Arduini, J., Young, D. and Simmonds, P. G.: Reconciling reported and unreported HFC emissions with atmospheric observations, Proc. Natl. Acad. Sci., 112(19), 5927 LP – 5931, doi:10.1073/pnas.1420247112, 2015.

Lynch, J. M., Cain, M., Pierrehumbert, R. T. and Allen, M.: Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants, Environ. Res. Lett., doi:10.1088/1748-9326/ab6d7e, 2020.

Macknick, J.: Energy and CO2 emission data uncertainties, Carbon Manag., doi:10.4155/cmt.11.10, 2011.

Marland, G.: Uncertainties in accounting for CO2 from fossil fuels, J. Ind. Ecol., doi:10.1111/j.1530-9290.2008.00014.x, 2008.

Marland, G., Brenkert, A. and Olivier, J.: CO2 from fossil fuel burning: A comparison of ORNL and EDGAR estimates of national emissions, Environ. Sci. Policy, doi:10.1016/S1462-9011(99)00018-0, 1999.

Marland, G., Hamal, K. and Jonas, M.: How Uncertain Are Estimates of CO2 Emissions?, J. Ind. Ecol., doi:10.1111/j.1530-9290.2009.00108.x, 2009.

Matricardi, E. A. T., Skole, D. L., Costa, O. B., Pedlowski, M. A., Samek, J. H. and Miguel, E. P.: Long-term forest degradation surpasses deforestation in the Brazilian Amazon, Science (80-.)., 369(6509), 1378 LP – 1382, doi:10.1126/science.abb3021, 2020.

McDuffie, E. E., Smith, S. J., O'Rourke, P., Tibrewal, K., Venkataraman, C., Marais, E. A., Zheng, B., Crippa, M., Brauer, M. and Martin, R. V: A global anthropogenic emission inventory of atmospheric pollutants from sector- and fuel-specific sources (1970–2017): an application of the Community Emissions Data System (CEDS), Earth Syst. Sci. Data, 12(4), 3413–3442, doi:10.5194/essd-12-3413-2020, 2020.

Minx, J. C., Baiocchi, G., Peters, G. P., Weber, C. L., Guan, D. B. and Hubacek, K.: A "Carbonizing Dragon": China's Fast Growing CO2 Emissions Revisited, Environ. Sci. Technol. Cited By - 184, 45, 9144–9153, doi:10.1021/es201497m Correspondence Address - jan.minx@pik-potsdam.de, 2011.

Minx, J. C., Lamb, W. F., Andrew, R. M., Canadell, J. G., Crippa, M., Döbbeling, N., Forster, P., Guizzardi, D., Olivier, J., Pongratz, J., Reisinger, A., Rigby, M., Peters, G., Saunois, M., Smith, S. J., Solazzo, E. and Tian, H.: A comprehensive dataset for global, regional and national greenhouse gas emissions by sector 1970-2019, , doi:10.5281/zenodo.5053056, 2021.

Monni, S., Perälä, P. and Regina, K.: Uncertainty in Agricultural CH4 AND N2O Emissions from Finland – Possibilities to Increase Accuracy in Emission Estimates, Mitig. Adapt. Strateg. Glob. Chang., 12(4), 545–571, doi:10.1007/s11027-006-4584-4, 2007.

Montzka, S. A. and Velders, G. J. M.: Chapter 2: Hydrofluorocarbons (HFCs), in Scientific Assessment of Ozone Depletion: 2018, World Meterological Organization, Geneva, Switzerland., 2018.

1305 Montzka, S. A., McFarland, M., Andersen, S. O., Miller, B. R., Fahey, D. W., Hall, B. D., Hu, L., Siso, C. and Elkins, J. W.: Recent Trends in Global Emissions of Hydrochlorofluorocarbons and Hydrofluorocarbons: Reflecting on the 2007 Adjustments to the Montreal Protocol, J. Phys. Chem. A, 119(19), 4439–4449, doi:10.1021/jp5097376, 2015.

Mosier, A. and Kroeze, C.: Potential impact on the global atmospheric N2O budget of the increased nitrogen input required to meet future global food demands, Chemosph. - Glob. Chang. Sci., 2(3–4), 465–473, doi:10.1016/S1465-9972(00)00039-8,

1310 2000.

Mosier, A., Kroeze, C., Nevison, C., Oenema, O. and Seitzinger, S.: Closing the global N 2 O budget : nitrous oxide emissions through the agricultural nitrogen cycle inventory methodology, Nutr. Cycl. Agroecosystems, 1998.

Mühle, J., Ganesan, A. L., Miller, B. R., Salameh, P. K., Harth, C. M., Greally, B. R., Rigby, M., Porter, L. W., Steele, L. P., Trudinger, C. M., Krummel, P. B., O'Doherty, S., Fraser, P. J., Simmonds, P. G., Prinn, R. G. and Weiss, R. F.:

1315 Perfluorocarbons in the global atmosphere: tetrafluoromethane, hexafluoroethane, and octafluoropropane, Atmos. Chem. Phys., 10(11), 5145–5164, doi:10.5194/acp-10-5145-2010, 2010.

Mühle, J., Trudinger, C. M., Western, L. M., Rigby, M., Vollmer, M. K., Park, S., Manning, A. J., Say, D., Ganesan, A., Steele, L. P., Ivy, D. J., Arnold, T., Li, S., Stohl, A., Harth, C. M., Salameh, P. K., McCulloch, A., O'Doherty, S., Park, M.-K., Jo, C. O., Young, D., Stanley, K. M., Krummel, P. B., Mitrevski, B., Hermansen, O., Lunder, C., Evangeliou, N., Yao, B., Kim, J.,

1320 Hmiel, B., Buizert, C., Petrenko, V. V, Arduini, J., Maione, M., Etheridge, D. M., Michalopoulou, E., Czerniak, M., Severinghaus, J. P., Reimann, S., Simmonds, P. G., Fraser, P. J., Prinn, R. G. and Weiss, R. F.: Perfluorocyclobutane (PFC-318, c-C4F8) in the global atmosphere, Atmos. Chem. Phys., 19(15), 10335–10359, doi:10.5194/acp-19-10335-2019, 2019.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T. and Zhang, H.: Chapter 8: Anthropogenic and Natural Radiative

1325 Forcing, in Climate Change 2013: The scientific basis. Contribution of Working Group I to the 5th Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, Cambridge University Press, Cambridge, UK, and New York, USA., 2013.

NASEM: Improving Measurement, Monitoring, Presentation of Results, and Development of Inventories. Improving

1330 Characterization of Anthropogenic Methane Emissions in the United States, Washington D.C., USA., 2018.

Nations, F. and A. O. of the U.: Global Forest Resources Assessment 2015., 2015.

O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J. F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K. and Sanderson, B. M.: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6, Geosci. Model Dev., doi:10.5194/gmd-9-3461-2016, 2016.

1335 O'Rourke, P. R., Smith, S. J., McDuffie, E. E., Crippa, M., Klimont, Z., Mott, A., Wang, S., Nicholson, M. B., Feng, L. and Hoesly, R. M.: CEDS v-2020-09-11 Pre-Release Emission Data 1975-2019., 2020.

O'Rourke, P. R., Smith, S. J., Mott, A., Ahsan, H., McDuffie, E. E., Crippa, M., Klimont, Z., McDonald, B., Wang, S., Nicholson, M. B., Feng, L. and Hoesly, R. M.: CEDS v_2021_04_21 Release Emission Data, , doi:10.5281/ZENODO.4741285, 2021.

1340 Obermeier, W. A., Nabel, J. E. M. S., Loughran, T., Hartung, K., Bastos, A., Havermann, F., Anthoni, P., Arneth, A., Goll, D. S., Lienert, S., Lombardozzi, D., Luyssaert, S., McGuire, P. C., Melton, J. R., Poulter, B., Sitch, S., Sullivan, M. O., Tian, H., Walker, A., Wiltshire, A. J., Zaehle, S. and Pongratz, J.: Modelled land use and land cover change emissions - A spatio-temporal comparison of different approaches, Earth Syst. Dyn., submitted, 2020.

Olivier, J. G. and Peters, J. A. H. W.: Trends in CO2 and total greenhouse gas emissions: 2019 Report, The Hague,
1345 Netherlands., 2020.

Olivier, J. G. J., Van Aardenne, J. A., Dentener, F. J., Pagliari, V., Ganzeveld, L. N. and Peters, J. A. H. W.: Recent trends in global greenhouse gas emissions:regional trends 1970–2000 and spatial distributionof key sources in 2000, Environ. Sci., 2(2–3), 81–99, doi:10.1080/15693430500400345, 2005.

Pedersen, J. S. T., van Vuuren, D. P., Aparício, B. A., Swart, R., Gupta, J. and Santos, F. D.: Variability in historical emissions
1350 trends suggests a need for a wide range of global scenarios and regional analyses, Commun. Earth Environ., doi:10.1038/s43247-020-00045-y, 2020.

Petrescu, A. M. R., Peters, G. P., Janssens-Maenhout, G., Ciais, P., Tubiello, F. N., Grassi, G., Nabuurs, G.-J., Leip, A., Carmona-Garcia, G., Winiwarter, W., Höglund-Isaksson, L., Günther, D., Solazzo, E., Kiesow, A., Bastos, A., Pongratz, J., Nabel, J. E. M. S., Conchedda, G., Pilli, R., Andrew, R. M., Schelhaas, M.-J. and Dolman, A. J.: European anthropogenic
1355 AFOLU greenhouse gas emissions: a review and benchmark data, Earth Syst. Sci. Data, 12(2), 961–1001, doi:10.5194/essd-12-961-2020, 2020a.

Petrescu, A. M. R., Qiu, C., Ciais, P., Thompson, R. L., Peylin, P., McGrath, M. J., Solazzo, E., Janssens-Maenhout, G., Tubiello, F. N., Bergamaschi, P., Brunner, D., Peters, G. P., Höglund-Isaksson, L., Regnier, P., Lauerwald, R., Bastviken, D., Tsuruta, A., Winiwarter, W., Patra, P. K., Kuhnert, M., Oreggioni, G. D., Crippa, M., Saunois, M., Perugini, L., Markkanen,
1360 T., Aalto, T., Groot Zwaaftink, C. D., Yao, Y., Wilson, C., Conchedda, G., Günther, D., Leip, A., Smith, P., Haussaire, J.-M., Leppänen, A., Manning, A. J., McNorton, J., Brockmann, P. and Dolman, H.: The consolidated European synthesis of CH4 and N2O emissions for EU27 and UK: 1990-2018, Earth Syst. Sci. Data Discuss., 2020, 1–78, doi:10.5194/essd-2020-367, 2020b.

Petrescu, A. M. R., McGrath, M. J., Andrew, R. M., Peylin, P., Peters, G. P., Ciais, P., Broquet, G., Tubiello, F. N., Gerbig,
1365 C., Pongratz, J., Janssens-Maenhout, G., Grassi, G., Nabuurs, G.-J., Regnier, P., Lauerwald, R., Kuhnert, M., Balcovič, J., Schelhaas, M.-J., Denier van der Gon, H. A. C., Solazzo, E., Qiu, C., Pilli, R., Konovalov, I. B., Houghton, R., Günther, D., Perugini, L., Crippa, M., Ganzenmüller, R., Luijkx, I. T., Smith, P., Munassar, S., Thompson, R. L., Conchedda, G., Monteil, G., Scholze, M., Karstens, U., Brokmann, P. and Dolman, H.: The consolidated European synthesis of CO2 emissions and removals for EU27 and UK: 1990-2018, Earth Syst. Sci. Data Discuss., 2020, 1–73, doi:10.5194/essd-2020-376, 2020c.

1370 Pongratz, J., Reick, C. H., Houghton, R. A. and House, J. I.: Terminology as a key uncertainty in net land use and land cover

change carbon flux estimates, Earth Syst. Dyn., 5(1), 177–195, doi:10.5194/esd-5-177-2014, 2014.

Prinn, R. G., Weiss, R. F., Arduini, J., Arnold, T., DeWitt, H. L., Fraser, P. J., Ganesan, A. L., Gasore, J., Harth, C. M., Hermansen, O., Kim, J., Krummel, P. B., Li, S., Loh, Z. M., Lunder, C. R., Maione, M., Manning, A. J., Miller, B. R., Mitrevski, B., Mühle, J., O'Doherty, S., Park, S., Reimann, S., Rigby, M., Saito, T., Salameh, P. K., Schmidt, R., Simmonds,

1375   P. G., Steele, L. P., Vollmer, M. K., Wang, R. H., Yao, B., Yokouchi, Y., Young, D. and Zhou, L.: History of chemically and radiatively important atmospheric gases from the Advanced Global Atmospheric Gases Experiment (AGAGE), Earth Syst. Sci. Data, 10(2), 985–1018, doi:10.5194/essd-10-985-2018, 2018.

Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., Korsbakken, J. I., Peters, G. P., Canadell, J. G., Jackson, R. B., Boden, T. A., Tans, P. P., Andrews, O. D., Arora, V. K., Bakker, D. C. E., Barbero, L., Becker,

1380   M., Betts, R. A., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Cosca, C. E., Cross, J., Currie, K., Gasser, T., Harris, I., Hauck, J., Haverd, V., Houghton, R. A., Hunt, C. W., Hurtt, G., Ilyina, T., Jain, A. K., Kato, E., Kautz, M., Keeling, R. F., Klein Goldewijk, K., Körtzinger, A., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lima, I., Lombardozzi, D., Metzl, N., Millero, F., Monteiro, P. M. S., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S. I., Nojiri, Y., Padin, X. A., Peregon, A., Pfeil, B., Pierrot, D., Poulter, B., Rehder, G., Reimer, J., Rödenbeck, C., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B.

1385   D., Tian, H., Tilbrook, B., Tubiello, F. N., van der Laan-Luijkx, I. T., van der Werf, G. R., van Heuven, S., Viovy, N., Vuichard, N., Walker, A. P., Watson, A. J., Wiltshire, A. J., Zaehle, S. and Zhu, D.: Global Carbon Budget 2017, Earth Syst. Sci. Data, 10(1), 405–448, doi:10.5194/essd-10-405-2018, 2018.

Le Quéré, C., Korsbakken, J. I., Wilson, C., Tosun, J., Andrew, R., Andres, R. J., Canadell, J. G., Jordan, A., Peters, G. P. and van Vuuren, D. P.: Drivers of declining CO 2 emissions in 18 developed economies, Nat. Clim. Chang., doi:10.1038/s41558-

1390   019-0419-7, 2019a.

Le Quéré, C., Korsbakken, J. I., Wilson, C., Tosun, J., Andrew, R., Andres, R. J., Canadell, J. G., Jordan, A., Peters, G. P. and van Vuuren, D. P.: Drivers of declining CO2 emissions in 18 developed economies, Nat. Clim. Chang., 9(3), 213–217, doi:10.1038/s41558-019-0419-7, 2019b.

Ramankutty, N., Gibbs, H. K., Achard, F., Defries, R., Foley, J. A. and Houghton, R. A.: Challenges to estimating carbon

1395   emissions from tropical deforestation, Glob. Chang. Biol., 13(1), 51–66, doi:https://doi.org/10.1111/j.1365-2486.2006.01272.x, 2007.

Reisinger, A., Meinshausen, M. and Manning, M.: Future changes in global warming potentials under representative concentration pathways, Environ. Res. Lett., doi:10.1088/1748-9326/6/2/024020, 2011.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko,

1400   O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L. A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J. C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A. and Tavoni, M.: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview, Glob. Environ. Chang., 42,

1405   153–168, doi:10.1016/j.gloenvcha.2016.05.009, 2017.

Rigby, M., Mühle, J., Miller, B. R., Prinn, R. G., Krummel, P. B., Steele, L. P., Fraser, P. J., Salameh, P. K., Harth, C. M., Weiss, R. F., Greally, B. R., O'Doherty, S., Simmonds, P. G., Vollmer, M. K., Reimann, S., Kim, J., Kim, K.-R., Wang, H. J., Olivier, J. G. J., Dlugokencky, E. J., Dutton, G. S., Hall, B. D. and Elkins, J. W.: History of atmospheric SF_6 from 1973 to 2008, Atmos. Chem. Phys., 10(21), 10305–10320, doi:10.5194/acp-10-10305-2010, 2010.

1410   Rigby, M., Prinn, R. G., O'Doherty, S., Miller, B. R., Ivy, D., Mühle, J., Harth, C. M., Salameh, P. K., Arnold, T., Weiss, R. F., Krummel, P. B., Steele, L. P., Fraser, P. J., Young, D. and Simmonds, P. G.: Recent and future trends in synthetic greenhouse gas radiative forcing, Geophys. Res. Lett., 41(7), 2623–2630, doi:https://doi.org/10.1002/2013GL059099, 2014.

Rogelj, J., Schaeffer, M., Meinshausen, M., Knutti, R., Alcamo, J., Riahi, K. and Hare, W.: Zero emission targets as long-term global goals for climate protection, Environ. Res. Lett., 10(10), 105007, doi:10.1088/1748-9326/10/10/105007, 2015.

1415   Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., Mundaca, L., Seferian, R. and Vilarino, M. V.: Mitigation Pathways Compatible With 1.5°C in the Context of Sustainable Development, Glob. Warm. 1.5°C. An IPCC Spec. Rep. [...], 2018a.

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., Van Vuuren, D. P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M.,

1420   Havlík, P., Humpenöder, F., Stehfest, E. and Tavoni, M.: Scenarios towards limiting global mean temperature increase below 1.5 °c, Nat. Clim. Chang., doi:10.1038/s41558-018-0091-3, 2018b.

Sanjuán, M. Á., Andrade, C., Mora, P. and Zaragoza, A.: Carbon dioxide uptake by cement-based materials: A spanish case study, Appl. Sci., doi:10.3390/app10010339, 2020.

Saunois, M., Bousquet, P., Poulter, B., Peregon, A., Ciais, P., Canadell, J. G., Dlugokencky, E. J., Etiope, G., Bastviken, D.,

1425   Houweling, S., Janssens-Maenhout, G., Tubiello, F. N., Castaldi, S., Jackson, R. B., Alexe, M., Arora, V. K., Beerling, D. J., Bergamaschi, P., Blake, D. R., Brailsford, G., Brovkin, V., Bruhwiler, L., Crevoisier, C., Crill, P., Covey, K., Curry, C., Frankenberg, C., Gedney, N., Höglund-Isaksson, L., Ishizawa, M., Ito, A., Joos, F., Kim, H. S., Kleinen, T., Krummel, P., Lamarque, J. F., Langenfelds, R., Locatelli, R., Machida, T., Maksyutov, S., McDonald, K. C., Marshall, J., Melton, J. R., Morino, I., Naik, V., O'Doherty, S., Parmentier, F. J. W., Patra, P. K., Peng, C., Peng, S., Peters, G. P., Pison, I., Prigent, C.,

1430   Prinn, R., Ramonet, M., Riley, W. J., Saito, M., Santini, M., Schroeder, R., Simpson, I. J., Spahni, R., Steele, P., Takizawa, A., Thornton, B. F., Tian, H., Tohjima, Y., Viovy, N., Voulgarakis, A., Van Weele, M., Van Der Werf, G. R., Weiss, R., Wiedinmyer, C., Wilton, D. J., Wiltshire, A., Worthy, D., Wunch, D., Xu, X., Yoshida, Y., Zhang, B., Zhang, Z. and Zhu, Q.: The global methane budget 2000-2012, Earth Syst. Sci. Data, doi:10.5194/essd-8-697-2016, 2016.

Saunois, M., R. Stavert, A., Poulter, B., Bousquet, P., G. Canadell, J., B. Jackson, R., A. Raymond, P., J. Dlugokencky, E.,

1435   Houweling, S., K. Patra, P., Ciais, P., K. Arora, V., Bastviken, D., Bergamaschi, P., R. Blake, D., Brailsford, G., Bruhwiler, L., M. Carlson, K., Carrol, M., Castaldi, S., Chandra, N., Crevoisier, C., M. Crill, P., Covey, K., L. Curry, C., Etiope, G., Frankenberg, C., Gedney, N., I. Hegglin, M., Höglund-Isaksson, L., Hugelius, G., Ishizawa, M., Ito, A., Janssens-Maenhout, G., M. Jensen, K., Joos, F., Kleinen, T., B. Krummel, P., L. Langenfelds, R., G. Laruelle, G., Liu, L., MacHida, T., Maksyutov,

S., C. McDonald, K., McNorton, J., A. Miller, P., R. Melton, J., Morino, I., Müller, J., Murguia-Flores, F., Naik, V., Niwa, Y.,
1440 Noce, S., O'Doherty, S., J. Parker, R., Peng, C., Peng, S., P. Peters, G., Prigent, C., Prinn, R., Ramonet, M., Regnier, P., J.
Riley, W., A. Rosentreter, J., Segers, A., J. Simpson, I., Shi, H., J. Smith, S., Paul Steele, L., F. Thornton, B., Tian, H., Tohjima,
Y., N. Tubiello, F., Tsuruta, A., Viovy, N., Voulgarakis, A., S. Weber, T., Van Weele, M., R. Van Der Werf, G., F. Weiss, R.,
Worthy, D., Wunch, D., Yin, Y., Yoshida, Y., Zhang, W., Zhang, Z., Zhao, Y., Zheng, B., Zhu, Q., Zhu, Q. and Zhuang, Q.:
The global methane budget 2000-2017, Earth Syst. Sci. Data, doi:10.5194/essd-12-1561-2020, 2020.

1445 Schwalm, C. R., Glendon, S. and Duffy, P. B.: RCP8.5 tracks cumulative CO_2 emissions, Proc. Natl.
Acad. Sci., 117(33), 19656 LP – 19657, doi:10.1073/pnas.2007117117, 2020.

Shcherbak, I., Millar, N. and Robertson, G. P.: Global metaanalysis of the nonlinear response of soil nitrous oxide (N 2O)
emissions to fertilizer nitrogen, Proc. Natl. Acad. Sci. U. S. A., doi:10.1073/pnas.1322434111, 2014.

Smith, C. J., Kramer, R. J., Myhre, G., Alterskjær, K., Collins, W., Sima, A., Boucher, O., Dufresne, J.-L., Nabat, P., Michou,
1450 M., Yukimoto, S., Cole, J., Paynter, D., Shiogama, H., O'Connor, F. M., Robertson, E., Wiltshire, A., Andrews, T., Hannay,
C., Miller, R., Nazarenko, L., Kirkevåg, A., Olivié, D., Fiedler, S., Lewinschal, A., Mackallah, C., Dix, M., Pincus, R. and
Forster, P. M.: Effective radiative forcing and adjustments in CMIP6 models, Atmos. Chem. Phys., 20(16), 9591–9618,
doi:10.5194/acp-20-9591-2020, 2020.

Solazzo, E., Crippa, M., Guizzardi, D., Muntean, M., Choulga, M. and Janssens-Maenhout, G.: Uncertainties in the EDGAR
1455 emission inventory of greenhouse gases, Atmos. Chem. Phys. Discuss., 2020, 1–46, doi:10.5194/acp-2020-1102, 2020.

Solazzo, E., Crippa, M., Guizzardi, D., Muntean, M., Choulga, M. and Janssens-Maenhout, G.: Uncertainties in the Emissions
Database for Global Atmospheric Research (EDGAR) emission inventory of greenhouse gases, Atmos. Chem. Phys., 21(7),
5655–5683, doi:10.5194/acp-21-5655-2021, 2021.

Steinfeld, H., Mooney, H., Schneider, F. and Neville, L.: Livestock in a Changing Landscape, Volume 1: Drivers,
1460 Consequences, and Responses, Bibliovault OAI Repos. Univ. Chicago Press, 2010.

Sterner, E. O. and Johansson, D. J. A.: The effect of climate–carbon cycle feedbacks on emission metrics, Environ. Res. Lett.,
12(3), 34019, 2017.

Strefler, J., Bauer, N., Kriegler, E., Popp, A., Giannousakis, A. and Edenhofer, O.: Between Scylla and Charybdis: Delayed
mitigation narrows the passage between large-scale CDR and high costs, Environ. Res. Lett., doi:10.1088/1748-9326/aab2ba,
1465 2018.

Syakila, A. and Kroeze, C.: The global nitrous oxide budget revisited, Greenh. Gas Meas. Manag.,
doi:10.3763/ghgmm.2010.0007, 2011.

Tian, H., Yang, J., Lu, C., Xu, R., Canadell, J. G., Jackson, R. B., Arneth, A., Chang, J., Chen, G., Ciais, P., Gerber, S., Ito,
A., Huang, Y., Joos, F., Lienert, S., Messina, P., Olin, S., Pan, S., Peng, C., Saikawa, E., Thompson, R. L., Vuichard, N.,
1470 Winiwarter, W., Zaehle, S., Zhang, B., Zhang, K. and Zhu, Q.: The Global N2O Model Intercomparison Project, Bull. Am.
Meteorol. Soc., 99(6), 1231–1251 [online] Available from: https://journals.ametsoc.org/view/journals/bams/99/6/bams-d-17-
0212.1.xml, 2018.

Tian, H., Yang, J., Xu, R., Lu, C., Canadell, J. G., Davidson, E. A., Jackson, R. B., Arneth, A., Chang, J., Ciais, P., Gerber, S., Ito, A., Joos, F., Lienert, S., Messina, P., Olin, S., Pan, S., Peng, C., Saikawa, E., Thompson, R. L., Vuichard, N., Winiwarter, W., Zaehle, S. and Zhang, B.: Global soil nitrous oxide emissions since the preindustrial era estimated by an ensemble of terrestrial biosphere models: Magnitude, attribution, and uncertainty, Glob. Chang. Biol., 25(2), 640–659, doi:10.1111/gcb.14514, 2019.

Tian, H., Xu, R., Canadell, J. G., Thompson, R. L., Winiwarter, W., Suntharalingam, P., Davidson, E. A., Ciais, P., Jackson, R. B., Janssens-Maenhout, G., Prather, M. J., Regnier, P., Pan, N., Pan, S., Peters, G. P., Shi, H., Tubiello, F. N., Zaehle, S., Zhou, F., Arneth, A., Battaglia, G., Berthet, S., Bopp, L., Bouwman, A. F., Buitenhuis, E. T., Chang, J., Chipperfield, M. P., Dangal, S. R. S., Dlugokencky, E., Elkins, J. W., Eyre, B. D., Fu, B., Hall, B., Ito, A., Joos, F., Krummel, P. B., Landolfi, A., Laruelle, G. G., Lauerwald, R., Li, W., Lienert, S., Maavara, T., MacLeod, M., Millet, D. B., Olin, S., Patra, P. K., Prinn, R. G., Raymond, P. A., Ruiz, D. J., van der Werf, G. R., Vuichard, N., Wang, J., Weiss, R. F., Wells, K. C., Wilson, C., Yang, J. and Yao, Y.: A comprehensive quantification of global nitrous oxide sources and sinks, Nature, doi:10.1038/s41586-020-2780-0, 2020.

Tubiello, F. N.: Greenhouse gas emissions due to agriculture, in Encyclopedia of Food Security and Sustainability, pp. 196–205, Elsevier., 2018.

Tubiello, F. N., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N. and Smith, P.: The FAOSTAT database of greenhouse gas emissions from agriculture, Environ. Res. Lett., doi:10.1088/1748-9326/8/1/015009, 2013.

Tubiello, F. N., Salvatore, M., Ferrara, A. F., House, J., Federici, S., Rossi, S., Biancalani, R., Condor Golec, R. D., Jacobs, H., Flammini, A., Prosperi, P., Cardenas-Galindo, P., Schmidhuber, J., Sanz Sanchez, M. J., Srivastava, N. and Smith, P.: The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990-2012, Glob. Chang. Biol., doi:10.1111/gcb.12865, 2015.

Tyukavina, A., Baccini, A., Hansen, M. C., Potapov, P. V., Stehman, S. V., Houghton, R. A., Krylov, A. M., Turubanova, S. and Goetz, S. J.: Aboveground carbon loss in natural and managed tropical forests from 2000 to 2012, Environ. Res. Lett., doi:10.1088/1748-9326/10/7/074002, 2015.

UNEP: The Emissions Gap Report 2020 - A UN Environment Synthesis Report, United Nations Environment Programme, Nairobi., 2020.

UNFCCC: Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on the third part of its first session, held in Katowice from 2 to 15 December 2018. Addendum, Part 2: Action taken by the Conference of the Parties servi, , 65, 2019.

UNFCCC, C.: Adoption of the Paris Agreement, United Nations Framework Convention on Climate Change, United Nations Office, Geneva (Switzerland)., 2015.

Wagner-Riddle, C., Congreves, K. A., Abalos, D., Berg, A. A., Brown, S. E., Ambadan, J. T., Gao, X. and Tenuta, M.: Globally important nitrous oxide emissions from croplands induced by freeze-thaw cycles, Nat. Geosci., doi:10.1038/ngeo2907, 2017.

Wang, Q., Zhou, F., Shang, Z., Ciais, P., Winiwarter, W., Jackson, R. B., Tubiello, F. N., Janssens-Maenhout, G., Tian, H.,

Cui, X., Canadell, J. G., Piao, S. and Tao, S.: Data-driven estimates of global nitrous oxide emissions from croplands, Natl. Sci. Rev., doi:10.1093/nsr/nwz087, 2020.

Wania, R., Melton, J. R., Hodson, E. L., Poulter, B., Ringeval, B., Spahni, R., Bohn, T., Avis, C. A., Chen, G., Eliseev, A. V.,
1510 Hopcroft, P. O., Riley, W. J., Subin, Z. M., Tian, H., Van Bodegom, P. M., Kleinen, T., Yu, Z. C., Singarayer, J. S., Zürcher, S., Lettenmaier, D. P., Beerling, D. J., Denisov, S. N., Prigent, C., Papa, F. and Kaplan, J. O.: Present state of global wetland extent and wetland methane modelling: Methodology of a model inter-comparison project (WETCHIMP), Geosci. Model Dev., doi:10.5194/gmd-6-617-2013, 2013.

van der Werf, G. R., Randerson, J. T., Giglio, L., van Leeuwen, T. T., Chen, Y., Rogers, B. M., Mu, M., van Marle, M. J. E.,
1515 Morton, D. C., Collatz, G. J., Yokelson, R. J. and Kasibhatla, P. S.: Global fire emissions estimates during 1997–2016, Earth Syst. Sci. Data, 9(2), 697–720, doi:10.5194/essd-9-697-2017, 2017.

Wiedinmyer, C., Akagi, S. K., Yokelson, R. J., Emmons, L. K., Al-Saadi, J. A., Orlando, J. J. and Soja, A. J.: The Fire INventory from NCAR (FINN): A high resolution global model to estimate the emissions from open burning, Geosci. Model Dev., doi:10.5194/gmd-4-625-2011, 2011.

1520 Wilkes, A., Reisinger, A., Wollenberg, E. and van Dijk, S.: Measurement, reporting and veri cation of livestock GHG emissions by developing countries in the UNFCCC: current practices and opportunities for improvement., Wageningen, the Netherlands., 2017.

Winiwarter, W., Höglund-Isaksson, L., Klimont, Z., Schöpp, W. and Amann, M.: Technical opportunities to reduce global anthropogenic emissions of nitrous oxide, Environ. Res. Lett., doi:10.1088/1748-9326/aa9ec9, 2018.

1525 WMO: Scientific Assessment of Ozone Depletion: 2018, Global Ozo., World Meterological Organization, Geneva, Switzerland., 2018.

World Bank: World Bank Development Indicators, [online] Available from: http://data.worldbank.org/ (Accessed 30 June 2021), 2021.

Xi, F., Davis, S. J., Ciais, P., Crawford-Brown, D., Guan, D., Pade, C., Shi, T., Syddall, M., Lv, J., Ji, L., Bing, L., Wang, J.,
1530 Wei, W., Yang, K. H., Lagerblad, B., Galan, I., Andrade, C., Zhang, Y. and Liu, Z.: Substantial global carbon uptake by cement carbonation, Nat. Geosci., doi:10.1038/ngeo2840, 2016.

Yang, S., Chang, B. X., Warner, M. J., Weber, T. S., Bourbonnais, A. M., Santoro, A. E., Kock, A., Sonnerup, R. E., Bullister, J. L., Wilson, S. T. and Bianchi, D.: Global reconstruction reduces the uncertainty of oceanic nitrous oxide emissions and reveals a vigorous seasonal cycle, Proc. Natl. Acad. Sci. U. S. A., doi:10.1073/pnas.1921914117, 2020.

1535 Yuan, J., Xiang, J., Liu, D., Kang, H., He, T., Kim, S., Lin, Y., Freeman, C. and Ding, W.: Rapid growth in greenhouse gas emissions from the adoption of industrial-scale aquaculture, Nat. Clim. Chang., doi:10.1038/s41558-019-0425-9, 2019.

Zhao, Y., Saunois, M., Bousquet, P., Lin, X., Berchet, A., Hegglin, M. I., Canadell, J. G., Jackson, R. B., Dlugokencky, E. J., Langenfelds, R. L., Ramonet, M., Worthy, D. and Zheng, B.: Influences of hydroxyl radicals (OH) on top-down estimates of the global and regional methane budgets, Atmos. Chem. Phys., doi:10.5194/acp-20-9525-2020, 2020.

1540