

1 **Global Carbon Budget 2023**

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## Abstract

Accurate assessment of anthropogenic carbon dioxide (CO<sub>2</sub>) emissions and their redistribution among the atmosphere, ocean, and terrestrial biosphere in a changing climate is critical to better understand the global carbon cycle, support the development of climate policies, and project future climate change. Here we describe and synthesise data sets and methodology to quantify the five major components of the global carbon budget and their uncertainties. Fossil CO<sub>2</sub> emissions (E<sub>FOS</sub>) are based on energy statistics and cement production data, while emissions from land-use change (E<sub>LUC</sub>), mainly deforestation, are based on land-use and land-use change data and bookkeeping models. Atmospheric CO<sub>2</sub> concentration is measured directly, and its growth rate (G<sub>ATM</sub>) is computed from the annual changes in concentration. The ocean CO<sub>2</sub> sink (S<sub>OCEAN</sub>) is estimated with global ocean biogeochemistry models and observation-based CO<sub>2</sub> products. The terrestrial CO<sub>2</sub> sink (S<sub>LAND</sub>) is estimated with dynamic global vegetation models. Additional lines of evidence on land and ocean sinks are provided by atmospheric inversions, atmospheric oxygen measurements and Earth System Models. The resulting carbon budget imbalance (B<sub>IM</sub>), the difference between the estimated total emissions and the estimated changes in the atmosphere, ocean, and terrestrial biosphere, is a measure of imperfect data and understanding of the contemporary carbon cycle. All uncertainties are reported as ±1σ.

For the year 2022, E<sub>FOS</sub> increased by 1.0% relative to 2021, with fossil emissions at 10.2 ± 0.5 GtC yr<sup>-1</sup> (9.9 ± 0.5 GtC yr<sup>-1</sup> when the cement carbonation sink is included), E<sub>LUC</sub> was 1.2 ± 0.7 GtC yr<sup>-1</sup>, for a total anthropogenic CO<sub>2</sub> emission (including the cement carbonation sink) of 11.1 ± 0.8 GtC yr<sup>-1</sup> (40.7 ± 3.2 GtCO<sub>2</sub> yr<sup>-1</sup>). Also, for 2022, G<sub>ATM</sub> was 4.6 ± 0.2 GtC yr<sup>-1</sup> (2.18 ± 0.1 ppm yr<sup>-1</sup>), S<sub>OCEAN</sub> was 2.8 ± 0.4 GtC yr<sup>-1</sup> and S<sub>LAND</sub> was 3.8 ± 0.8 GtC yr<sup>-1</sup>, with a B<sub>IM</sub> of -0.1 GtC yr<sup>-1</sup> (i.e. total estimated sources marginally too low or sinks too high). The global atmospheric CO<sub>2</sub> concentration averaged over 2022 reached 417.1 ± 0.1 ppm. Preliminary data for 2023, suggest an increase in E<sub>FOS</sub> relative to 2022 of +1.2% (0.2% to 2.2%) globally, and atmospheric CO<sub>2</sub> concentration reaching 419.2 ppm, more than 50% above pre-industrial level (around 278 ppm in 1750). Overall, the mean and trend in the components of the global carbon budget are consistently estimated over the period 1959–2022, with a near-zero overall budget imbalance, although discrepancies of up to around 1 GtC yr<sup>-1</sup> persist for the representation of annual to semi-decadal variability in CO<sub>2</sub> fluxes. Comparison of estimates from multiple approaches and observations shows: (1) a persistent large uncertainty in the estimate of land-use changes emissions, (2) a low agreement between the different methods on the magnitude of the land CO<sub>2</sub> flux in the northern extra-tropics, and (3) a discrepancy between the different methods on the strength of the ocean sink over the last decade. This living data update documents changes in the methods and data sets used in this new global carbon budget and the progress in understanding of the global carbon cycle compared with previous publications of this data set. The data presented in this work are available at <https://doi.org/10.18160/GCP-2023> (Friedlingstein et al., 2023).

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828 **Executive Summary**

829 Global fossil CO<sub>2</sub> emissions (including cement carbonation) **are expected to further increase in 2023, to**  
830 **1.5% above their pre-COVID-19 pandemic 2019 level.** The 2022 emission increase was 0.08 GtC yr<sup>-1</sup> (0.31  
831 GtCO<sub>2</sub> yr<sup>-1</sup>) relative to 2021, bringing 2022 fossil CO<sub>2</sub> emissions to 9.9 ± 0.5 GtC yr<sup>-1</sup> (36.3 ± 1.8 GtCO<sub>2</sub> yr<sup>-1</sup>),  
832 virtually equal to the emissions level of 2019. Preliminary estimates based on data available suggest fossil CO<sub>2</sub>  
833 emissions to increase further in 2023, by 1.2% relative to 2022 (0.2% to 2.2%), bringing emissions to 10.0 GtC  
834 yr<sup>-1</sup> (36.8 GtCO<sub>2</sub> yr<sup>-1</sup>), 1.5% above the 2019 level.

835 Emissions from coal, oil, and gas in 2023 are expected to be slightly above their 2022 levels (by 1.1%, 1.8% and  
836 0.3% respectively). Regionally, fossil emissions in 2022 are expected to decrease by 7.1% in the European  
837 Union (0.7 GtC, 2.6 GtCO<sub>2</sub>), and by 3.4% in the United States (1.3 GtC, 4.9 GtCO<sub>2</sub>), but to increase by 4.0% in  
838 China (3.2 GtC, 11.9 GtCO<sub>2</sub>), 8.0% in India (0.8 GtC, 3.1 GtCO<sub>2</sub>) and 0.9% for the rest of the world (4.2 GtC,  
839 15.2 GtCO<sub>2</sub>).

840 Fossil CO<sub>2</sub> emissions decreased in 18 countries during the decade 2013–2022. Altogether, these 18 countries  
841 contribute about 1.9 GtC yr<sup>-1</sup> (7.1 GtCO<sub>2</sub>) fossil fuel CO<sub>2</sub> emissions over the last decade, representing about  
842 20% of world CO<sub>2</sub> fossil emissions.

843 Global CO<sub>2</sub> emissions from land-use, land-use change, and forestry (LUC) averaged 1.3 ± 0.7 GtC yr<sup>-1</sup>  
844 (4.7 ± 2.6 GtCO<sub>2</sub> yr<sup>-1</sup>) for the 2013–2022 period with a preliminary projection for 2023 of 1.1 ± 0.7 GtC yr<sup>-1</sup>  
845 (4.0 ± 2.6 GtCO<sub>2</sub> yr<sup>-1</sup>). A small decrease over the past two decades is not robust given the large model  
846 uncertainty. Emissions from deforestation, the main driver of global gross sources, remain high at around 1.9  
847 GtC yr<sup>-1</sup> over the 2013–2022 period, highlighting the strong potential of halting deforestation for emissions  
848 reductions. Sequestration of 1.3 GtC yr<sup>-1</sup> through re-/afforestation and forestry offsets two third of the  
849 deforestation emissions. Emissions from other land-use transitions and from peat drainage and peat fire add  
850 further, smaller contributions. The highest emitters during 2013–2022 in descending order were Brazil,  
851 Indonesia, and the Democratic Republic of the Congo, with these 3 countries contributing more than half of  
852 global land-use CO<sub>2</sub> emissions.

853 The remaining carbon budget for a 50% likelihood to limit global warming to 1.5°C, 1.7°C and 2°C has  
854 respectively reduced to 75 GtC (275 GtCO<sub>2</sub>), 175 GtC (625 GtCO<sub>2</sub>) and 315 GtC (1150 GtCO<sub>2</sub>) from the  
855 beginning of 2024, equivalent to around 7, 15 and 28 years, assuming 2023 emissions levels. Total  
856 anthropogenic emissions were 11.1 GtC yr<sup>-1</sup> (40.7 GtCO<sub>2</sub> yr<sup>-1</sup>) in 2022, with a similar preliminary estimate of  
857 11.2 GtC yr<sup>-1</sup> (40.9 GtCO<sub>2</sub> yr<sup>-1</sup>) for 2023.

858 The concentration of CO<sub>2</sub> in the atmosphere is set to reach 419.2 ppm in 2023, 51% above pre-industrial  
859 levels. The atmospheric CO<sub>2</sub> growth was 5.2 ± 0.02 GtC yr<sup>-1</sup> during the decade 2013–2022 (47% of total CO<sub>2</sub>  
860 emissions) with a preliminary 2023 growth rate estimate of around 4.0 GtC (1.89 ppm).

861 The ocean CO<sub>2</sub> sink resumed a more rapid growth in the past two decades after low or no growth during  
862 the 1991–2002 period, overlaid with imprints of climate variability. The estimates based on pCO<sub>2</sub>-products  
863 and models diverge with the growth of the ocean CO<sub>2</sub> sink in the past decade being a factor 2.5 larger than in the

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... [22]

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047 [models. This](#) discrepancy in the trend originates from all latitudes but is largest in the Southern Ocean. The  
048 ocean CO<sub>2</sub> sink was 2.9 ± 0.4 GtC yr<sup>-1</sup> during the decade [2013-2022](#) (26% of total CO<sub>2</sub> emissions), [and did not](#)  
049 [grow since 2019 due to a triple La Niña event. A similar value of 2.9 GtC yr<sup>-1</sup> is preliminarily estimated for](#)  
050 [2023, which marks an increase in the sink compared to the last two years due to the transition from La Niña to](#)  
051 [El Niño conditions in 2023.](#)

052 **The land CO<sub>2</sub> sink continued to increase during the [2013-2022](#) period primarily in response to increased**  
053 **atmospheric CO<sub>2</sub>, albeit with large interannual variability.** The land CO<sub>2</sub> sink was 3.3 ± 0.8 GtC yr<sup>-1</sup> during  
054 the [2013-2022](#) decade ([31%](#) of total CO<sub>2</sub> emissions), 0.4 GtC yr<sup>-1</sup> larger than during the previous decade (2000-  
055 2009), with a preliminary [2023](#) estimate of around 3.4 GtC yr<sup>-1</sup>. Year to year variability in the land sink is about  
056 1 GtC yr<sup>-1</sup> and dominates the year-to-year changes in the global atmospheric CO<sub>2</sub> concentration, implying that  
057 small annual changes in anthropogenic emissions (such as the fossil fuel emission decrease in 2020) are hard to  
058 detect in the atmospheric CO<sub>2</sub> observations.

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1073 1 Introduction

1074 The concentration of carbon dioxide (CO<sub>2</sub>) in the atmosphere has increased from approximately 278 parts per  
1075 million (ppm) in 1750 (Gulev et al., 2021), the beginning of the Industrial Era, to ~~417.1 ± 0.1 ppm in 2022~~ (Lan  
1076 et al., 2023; Figure 1). The atmospheric CO<sub>2</sub> increase above pre-industrial levels was, initially, primarily caused  
1077 by the release of carbon to the atmosphere from deforestation and other land-use change activities (Canadell et  
1078 al., 2021). While emissions from fossil fuels started before the Industrial Era, they became the dominant source  
1079 of anthropogenic emissions to the atmosphere from around 1950 and their relative share has continued to  
1080 increase until present. Anthropogenic emissions occur on top of an active natural carbon cycle that circulates  
1081 carbon between the reservoirs of the atmosphere, ocean, and terrestrial biosphere on time scales from sub-daily  
1082 to millennia, while exchanges with geologic reservoirs occur at longer timescales (Archer et al., 2009).

1083 The global carbon budget (GCB) presented here refers to the mean, variations, and trends in the perturbation of  
1084 CO<sub>2</sub> in the environment, referenced to the beginning of the Industrial Era (defined here as 1750). This paper  
1085 describes the components of the global carbon cycle over the historical period with a stronger focus on the  
1086 recent period (since 1958, onset of robust atmospheric CO<sub>2</sub> measurements), the last decade (2013-2022), the last  
1087 year (2022) and the current year (2023). Finally, it provides cumulative emissions from fossil fuels and land-use  
1088 change since the year 1750 (the pre-industrial period), and since the year 1850 (the reference year for historical  
1089 simulations in IPCC AR6) (Eyring et al., 2016).

1090 We quantify the input of CO<sub>2</sub> to the atmosphere by emissions from human activities, the growth rate of  
1091 atmospheric CO<sub>2</sub> concentration, and the resulting changes in the storage of carbon in the land and ocean  
1092 reservoirs in response to increasing atmospheric CO<sub>2</sub> levels, climate change and variability, and other  
1093 anthropogenic and natural changes (Figure 2). An understanding of this perturbation budget over time and the  
1094 underlying variability and trends of the natural carbon cycle is necessary to understand the response of natural  
1095 sinks to changes in climate, CO<sub>2</sub> and land-use change drivers, and to quantify emissions compatible with a given  
1096 climate stabilisation target.

1097 The components of the CO<sub>2</sub> budget that are reported annually in this paper include separate and independent  
1098 estimates for the CO<sub>2</sub> emissions from (1) fossil fuel combustion and oxidation from all energy and industrial  
1099 processes; also including cement production and carbonation (E<sub>FOS</sub>; GtC yr<sup>-1</sup>) and (2) the emissions resulting  
1100 from deliberate human activities on land, including those leading to land-use change (E<sub>LUC</sub>; GtC yr<sup>-1</sup>); and their  
1101 partitioning among (3) the growth rate of atmospheric CO<sub>2</sub> concentration (G<sub>ATM</sub>; GtC yr<sup>-1</sup>), and the uptake of  
1102 CO<sub>2</sub> (the ‘CO<sub>2</sub> sinks’) in (4) the ocean (S<sub>OCEAN</sub>; GtC yr<sup>-1</sup>) and (5) on land (S<sub>LAND</sub>; GtC yr<sup>-1</sup>). The CO<sub>2</sub> sinks as  
1103 defined here conceptually include the response of the land (including inland waters and estuaries) and ocean  
1104 (including coastal and marginal seas) to elevated CO<sub>2</sub> and changes in climate and other environmental  
1105 conditions, although in practice not all processes are fully accounted for (see Section 2.10). Global emissions  
1106 and their partitioning among the atmosphere, ocean and land are in balance in the real world. Due to the  
1107 combination of imperfect spatial and/or temporal data coverage, errors in each estimate, and smaller terms not  
1108 included in our budget estimate (discussed in Section 2.10), the independent estimates (1) to (5) above do not

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necessarily add up to zero. We therefore assess a set of additional lines of evidence derived from global atmospheric inversion system results (Section 2.7), observed changes in oxygen concentration (Section 2.8) and Earth System Models (ESMs) simulations (Section 2.9), all of which closing the global carbon balance. We also estimate a budget imbalance ( $B_{IM}$ ), which is a measure of the mismatch between the estimated emissions and the estimated changes in the atmosphere, land and ocean, as follows:

$$B_{IM} = E_{FOS} + E_{LUC} - (G_{ATM} + S_{OCEAN} + S_{LAND}) \quad (1)$$

$G_{ATM}$  is usually reported in ppm yr<sup>-1</sup>, which we convert to units of carbon mass per year, GtC yr<sup>-1</sup>, using 1 ppm = 2.124 GtC (Ballantyne et al., 2012; Table 1). All quantities are presented in units of gigatonnes of carbon (GtC, 10<sup>15</sup> gC), which is the same as petagrams of carbon (PgC; Table 1). Units of gigatonnes of CO<sub>2</sub> (or billion tonnes of CO<sub>2</sub>) used in policy are equal to 3.664 multiplied by the value in units of GtC.

We also quantify  $E_{FOS}$  and  $E_{LUC}$  by country, including both territorial and consumption-based accounting for  $E_{FOS}$  (see Section 2), and discuss missing terms from sources other than the combustion of fossil fuels (see Section 2.10, Appendix D1 and D2).

We now assess carbon dioxide removal (CDR) (see Sect. 2.2 and 2.3). Land-based CDR is significant, but already accounted for in  $E_{LUC}$  in equation (1) (Sect 3.2.2). Other CDR methods, not based on vegetation, are currently several orders of magnitude smaller than the other components of the budget (Sect. 3.3), hence these are not included in equation (1), or in the global carbon budget tables or figures (with the exception of Figure 2 where CDR is shown primarily for illustrative purpose).

The global CO<sub>2</sub> budget has been assessed by the Intergovernmental Panel on Climate Change (IPCC) in all assessment reports (Prentice et al., 2001; Schimel et al., 1995; Watson et al., 1990; Denman et al., 2007; Ciais et al., 2013; Canadell et al., 2021), and by others (e.g. Ballantyne et al., 2012). The Global Carbon Project (GCP, www.globalcarbonproject.org, last access: 27 September 2023) has coordinated this cooperative community effort for the annual publication of global carbon budgets for the year 2005 (Raupach et al., 2007; including fossil emissions only), year 2006 (Canadell et al., 2007), year 2007 (GCP, 2008), year 2008 (Le Quéré et al., 2009), year 2009 (Friedlingstein et al., 2010), year 2010 (Peters et al., 2012a), year 2012 (Le Quéré et al., 2013; Peters et al., 2013), year 2013 (Le Quéré et al., 2014), year 2014 (Le Quéré et al., 2015a; Friedlingstein et al., 2014), year 2015 (Jackson et al., 2016; Le Quéré et al., 2015b), year 2016 (Le Quéré et al., 2016), year 2017 (Le Quéré et al., 2018a; Peters et al., 2017), year 2018 (Le Quéré et al., 2018b; Jackson et al., 2018), year 2019 (Friedlingstein et al., 2019; Jackson et al., 2019; Peters et al., 2020), year 2020 (Friedlingstein et al., 2020; Le Quéré et al., 2021), year 2021 (Friedlingstein et al., 2022a; Jackson et al., 2022) and most recently the year 2022 (Friedlingstein et al., 2022b). Each of these papers updated previous estimates with the latest available information for the entire time series.

We adopt a range of  $\pm 1$  standard deviation ( $\sigma$ ) to report the uncertainties in our global estimates, representing a likelihood of 68% that the true value will be within the provided range if the errors have a gaussian distribution, and no bias is assumed. This choice reflects the difficulty of characterising the uncertainty in the CO<sub>2</sub> fluxes between the atmosphere and the ocean and land reservoirs individually, particularly on an annual basis, as well as the difficulty of updating the CO<sub>2</sub> emissions from land-use change. A likelihood of 68% provides an

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1166 indication of our current capability to quantify each term and its uncertainty given the available information.  
1167 The uncertainties reported here combine statistical analysis of the underlying data, assessments of uncertainties  
1168 in the generation of the data sets, and expert judgement of the likelihood of results lying outside this range. The  
1169 limitations of current information are discussed in the paper and have been examined in detail elsewhere  
1170 (Ballantyne et al., 2015; Zscheischler et al., 2017). We also use a qualitative assessment of confidence level to  
1171 characterise the annual estimates from each term based on the type, amount, quality, and consistency of the  
1172 [different lines of](#) evidence as defined by the IPCC (Stocker et al., 2013).

1173 This paper provides a detailed description of the data sets and methodology used to compute the global carbon  
1174 budget estimates for the industrial period, from 1750 to [2023](#), and in more detail for the period since 1959. This  
1175 paper is updated every year using the format of ‘living data’ to keep a record of budget versions and the changes  
1176 in new data, revision of data, and changes in methodology that lead to changes in estimates of the carbon  
1177 budget. Additional materials associated with the release of each new version will be posted at the Global Carbon  
1178 Project (GCP) website (<http://www.globalcarbonproject.org/carbonbudget>, last access: [27 September 2023](#)),  
1179 with fossil fuel emissions also available through the Global Carbon Atlas (<http://www.globalcarbonatlas.org>,  
1180 last access: [27 September 2023](#)). All underlying data used to produce the budget can also be found at  
1181 <https://globalcarbonbudget.org/> (last access: [27 September 2023](#)). With this approach, we aim to provide the  
1182 highest transparency and traceability in the reporting of CO<sub>2</sub>, the key driver of climate change.

1183 **2 Methods**

1184 Multiple organisations and research groups around the world generated the original measurements and data used  
1185 to complete the global carbon budget. The effort presented here is thus mainly one of synthesis, where results  
1186 from individual groups are collated, analysed, and evaluated for consistency. We facilitate access to original  
1187 data with the understanding that primary data sets will be referenced in future work (see Table 2 for how to cite  
1188 the data sets, [and Section on data availability](#)). Descriptions of the measurements, models, and methodologies  
1189 follow below, [with more](#) detailed descriptions of each component provided [as Supplementary Information](#),  
1190 [Appendix C](#).

1191 This is the [18th](#) version of the global carbon budget and the [12th](#) revised version in the format of a living data  
1192 update in Earth System Science Data. It builds on the latest published global carbon budget of Friedlingstein et  
1193 al. ([2022b](#)). The main changes [this year](#) are: the inclusion of (1) data to year [2022](#) and a projection for the global  
1194 carbon budget for year [2023](#); (2) [CO<sub>2</sub> uptake from Carbon Dioxide Removal \(CDR\)](#); (3) [land and ocean net](#)  
1195 [carbon fluxes](#) estimates [from changes in atmospheric oxygen concentration](#); (4) [land and ocean net carbon](#)  
1196 [fluxes estimates from ESMs](#); and (5) revised method to estimate the current year (2023) atmospheric CO<sub>2</sub>. The  
1197 main [methodological differences between recent annual carbon budgets \(2019 to 2023\)](#) are summarised in Table  
1198 [3](#) and previous changes since 2006 are provided in Table A8.

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## 2.1 Fossil CO<sub>2</sub> emissions (E<sub>FOS</sub>)

### 2.1.1 Historical period 1850-2022

The estimates of global and national fossil CO<sub>2</sub> emissions (E<sub>FOS</sub>) include the oxidation of fossil fuels through both combustion (e.g., transport, heating) and chemical oxidation (e.g. carbon anode decomposition in aluminium refining) activities, and the decomposition of carbonates in industrial processes (e.g. the production of cement). We also include CO<sub>2</sub> uptake from the cement carbonation process. Several emissions sources are not estimated or not fully covered: coverage of emissions from lime production are not global, and decomposition of carbonates in glass and ceramic production are included only for the “Annex 1” countries of the United Nations Framework Convention on Climate Change (UNFCCC) for lack of activity data. These omissions are considered to be minor. Short-cycle carbon emissions - for example from combustion of biomass - are not included here but are accounted for in the CO<sub>2</sub> emissions from land use (see [Section 2.2](#)).

Our estimates of fossil CO<sub>2</sub> emissions [rely](#) on data collection by many other parties. Our goal is to produce the best estimate of this flux, and we therefore use a prioritisation framework to combine data from different sources that have used different methods, while being careful to avoid double counting and undercounting of emissions sources. The CDIAC-FF emissions dataset, derived largely from UN energy data, forms the foundation, and we extend emissions to year Y-1 using energy growth rates reported by [the Energy Institute \(a dataset formally produced by BP\)](#). We then proceed to replace estimates using data from what we consider to be superior sources, for example Annex 1 countries’ official submissions to the UNFCCC. All data points are potentially subject to revision, not just the latest year. For full details see Andrew and Peters ([2022](#)).

Other estimates of global fossil CO<sub>2</sub> emissions exist, and these are compared by Andrew (2020a). The most common reason for differences in estimates of global fossil CO<sub>2</sub> emissions is a difference in which emissions sources are included in the datasets. Datasets such as those published by the energy company BP, the US Energy Information Administration, and the International Energy Agency’s ‘CO<sub>2</sub> emissions from fuel combustion’ are all generally limited to emissions from combustion of fossil fuels. In contrast, datasets such as PRIMAP-hist, CEDS, EDGAR, and GCP’s dataset aim to include all sources of fossil CO<sub>2</sub> emissions. See Andrew (2020a) for detailed comparisons and discussion.

Cement absorbs CO<sub>2</sub> from the atmosphere over its lifetime, a process known as ‘cement carbonation’. We estimate this CO<sub>2</sub> sink, from 1931, onwards as the average of two studies in the literature (Cao et al., 2020; Guo et al., 2021). Both studies use the same model, developed by Xi et al. (2016), with different parameterisations and input data, with the estimate of Guo and colleagues being a revision of Xi et al. (2016). The trends of the two studies are very similar. Since carbonation is a function of both current and previous cement production, we extend these estimates to 2022 by using the growth rate derived from the smoothed cement emissions (10-year smoothing) fitted to the carbonation data. [In the present budget, we always include the cement carbonation carbon sink in the fossil CO<sub>2</sub> emission component \(E<sub>FOS</sub>\).](#)

We use the Kaya Identity for a simple decomposition of CO<sub>2</sub> emissions into the key drivers (Raupach et al., 2007). While there are variations (Peters et al., 2017), we focus here on a decomposition of CO<sub>2</sub> emissions into

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1270 population, GDP per person, energy use per GDP, and CO<sub>2</sub> emissions per energy. Multiplying these individual  
1271 components together returns the CO<sub>2</sub> emissions. Using the decomposition, it is possible to attribute the change  
1272 in CO<sub>2</sub> emissions to the change in each of the drivers. This method gives a first-order understanding of what  
1273 causes CO<sub>2</sub> emissions to change each year.

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274 **2.1.2 2023 projection**

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275 We provide a projection of global fossil CO<sub>2</sub> emissions in 2022 by combining separate projections for China,  
276 USA, EU, India, and for all other countries combined. The methods are different for each of these. For China we  
277 combine monthly fossil fuel production data from the National Bureau of Statistics, and trade data from the  
278 Customs Administration, giving us partial data for the growth rates to date of natural gas, petroleum, and  
279 cement, and of the apparent consumption itself for raw coal. We then use a regression model to project full-year  
280 emissions based on historical observations. For the USA our projection is taken directly from the Energy  
281 Information Administration's (EIA) Short-Term Energy Outlook (EIA, 2023), combined with the year-to-date  
282 growth rate of cement clinker production. For the EU we use monthly energy data from Eurostat to derive  
283 estimates of monthly CO<sub>2</sub> emissions through July, with coal emissions extended through September using a  
284 statistical relationship with reported electricity generation from coal and other factors. For natural gas we use  
285 Holt-Winters to project the last four months of the year. EU emissions from oil are derived using the EIA's  
286 projection of oil consumption for Europe. EU cement emissions are based on available year-to-date data from  
287 three of the largest producers, Germany, Poland, and Spain. India's projected emissions are derived from  
288 estimates through August (July for coal) using the methods of Andrew (2020b) and extrapolated assuming  
289 seasonal patterns from before 2019. Emissions for the rest of the world are derived using projected growth in  
290 economic production from the IMF (2023) combined with extrapolated changes in emissions intensity of  
291 economic production. More details on the E<sub>FOS</sub> methodology and its 2023 projection can be found in Appendix  
1292 C.1.

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Deleted: very high uncertainty in European energy markets in 2022, we forego our usual history-based projection techniques and use instead

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293 **2.2 CO<sub>2</sub> emissions from land-use, land-use change and forestry (E<sub>LUC</sub>)**

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294 **2.2.1 Historical period 1850-2022**

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295 The net CO<sub>2</sub> flux from land-use, land-use change and forestry (E<sub>LUC</sub>, called land-use change emissions in the  
296 rest of the text) includes CO<sub>2</sub> fluxes from deforestation, afforestation, logging and forest degradation (including  
297 harvest activity), shifting cultivation (cycle of cutting forest for agriculture, then abandoning), and regrowth of  
298 forests (following wood harvest or agriculture abandonment). Emissions from peat burning and peat drainage  
299 are added from external datasets, peat drainage being averaged from three spatially explicit independent datasets  
1300 (see Appendix C.2.1).

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301 Three bookkeeping approaches (updated estimates each of BLUE (Hansis et al., 2015), OSCAR (Gasser et al.,  
302 2020), and H&C2023 (Houghton and Castanho, 2023)) were used to quantify gross emissions and gross  
303 removals and the resulting net E<sub>LUC</sub>. Uncertainty estimates were derived from the Dynamic Global Vegetation  
304 Models (DGVMs) ensemble for the time period prior to 1960, and using for the recent decades an uncertainty  
1305 range of ±0.7 GtC yr<sup>-1</sup>, which is a semi-quantitative measure for annual and decadal emissions and reflects our

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best value judgement that there is at least 68% chance ( $\pm 1\sigma$ ) that the true land-use change emission lies within the given range, for the range of processes considered here.

Our  $E_{LUC}$  estimates follow the definition of global carbon cycle models of CO<sub>2</sub> fluxes related to land use and land management and differ from IPCC definitions adopted in National GHG Inventories (NGHGI) for reporting under the UNFCCC, which additionally generally include, through adoption of the IPCC so-called managed land proxy approach, the terrestrial fluxes occurring on all land that countries define as managed. This partly includes fluxes due to environmental change (e.g. atmospheric CO<sub>2</sub> increase), which are part of  $S_{LAND}$  in our definition. This causes the global emission estimates to be smaller for NGHGI than for the global carbon budget definition (Grassi et al., 2018). The same is the case for the Food Agriculture Organization (FAO) estimates of carbon fluxes on forest land, which include both anthropogenic and natural sources on managed land (Tubiello et al., 2021). We translate the two definitions to each other, to provide a comparison of the anthropogenic carbon budget to the official country reporting to the climate convention.

$E_{LUC}$  contains a range of fluxes that are related to Carbon Dioxide Removal (CDR). CDR can be defined as the set of anthropogenic activities that remove CO<sub>2</sub> from the atmosphere and store it in durable form, such as in forest biomass and soils, long-lived products, or in geological or ocean reservoirs. We quantify vegetation-based CDR that is implicitly or explicitly captured by land-use fluxes consistent with our updated model estimates (CDR not based on vegetation is discussed in Section 2.3; IPCC, 2023). We quantify re/afforestation from the three bookkeeping estimates by separating forest regrowth in shifting cultivation cycles from permanent increases in forest cover (see Appendix C.2.1). The latter count as CDR, but it should be noted that the permanence of the storage under climate risks such as fire is increasingly questioned. Other CDR activities contained in  $E_{LUC}$  include the transfer of carbon to harvested wood products (HWP), which is represented by the bookkeeping models with varying details concerning product usage and their lifetimes; bioenergy with carbon capture and storage (BECCS); and biochar production. Bookkeeping and TRENDY models currently only represent BECCS and biochar with regard to the CO<sub>2</sub> removal through photosynthesis, but not for the durable storage. HWP, BECCS, and biochar are typically counted as CDR when the transfer to the durable storage site occurs and not when the CO<sub>2</sub> is removed from the atmosphere, which complicates a direct comparison to the global carbon budgets approach to quantify annual fluxes to and from the atmosphere. Estimates for CDR through HWP, BECCS, and biochar are thus not indicated in this budget, but can be found elsewhere (see Section 3.2.2).

### 2.2.2 2023 Projection

We project the 2023 land-use emissions for BLUE, H&C2023, and OSCAR, based on their  $E_{LUC}$  estimates for 2022 and adding the change in carbon emissions from peat fires, and tropical deforestation and degradation fires (2023 emissions relative to 2022 emissions) estimated using active fire data (MCD14ML; Giglio et al., 2016). Peat drainage is assumed to be unaltered as it has low interannual variability. More details on the  $E_{LUC}$  methodology can be found in Appendix C.2.

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386 **2.3 Carbon Dioxide Removal (CDR) not based on vegetation**

387 CDR not based on terrestrial vegetation currently relies on enhanced rock weathering and Direct Air Carbon

388 Capture and Storage (DACCS) projects. The majority of this (58%) derives from a single project: Climeworks’

389 Orca DACCS plant based in Hellisheidi, Iceland. The remainder is generated by 13 small-scale projects

390 including, for example, 500 tons of carbon dioxide sequestered through the spreading of crushed olivine on

391 agricultural areas by Eion Carbon. We use data from the State of CDR Report (Smith et al., 2023), which

392 quantifies all currently deployed CDR methods, including the land-use related activities already covered by

393 Section 2.2. The State of CDR Report (Smith et al., 2023) combines estimates of carbon storage in managed

394 land derived from NGHGI data with project-by-project storage rates obtained through 20 extant CDR databases

395 and registries (status as of mid-year 2022) by Powis et al. (2023). They assessed the data quality on existing

396 CDR projects to be poor, suffering from fragmentation, different reporting standards, limited geographical

397 coverage, and inclusion of a number of pilot plants with uncertain lifespans. As a consequence, these numbers

398 could change substantially from year-to-year in the near-term.

## 399 2.4 Growth rate in atmospheric CO<sub>2</sub> concentration (G<sub>ATM</sub>)

### 400 2.4.1 Historical period 1850–2022

401 The rate of growth of the atmospheric CO<sub>2</sub> concentration is provided for years 1959–2022 by the US National

402 Oceanic and Atmospheric Administration Global Monitoring Laboratory (NOAA/GML; [Lan et al., 2023](#)),

403 which is updated from Ballantyne et al. (2012) and includes recent revisions to the calibration scale of

404 atmospheric CO<sub>2</sub> measurements (Hall et al., 2021). For the 1959–1979 period, the global growth rate is based on

405 measurements of atmospheric CO<sub>2</sub> concentration averaged from the Mauna Loa and South Pole stations, as

406 observed by the CO<sub>2</sub> Program at Scripps Institution of Oceanography (Keeling et al., 1976). For the 1980–2021

407 time period, the global growth rate is based on the average of multiple stations selected from the marine

408 boundary layer sites with well-mixed background air (Ballantyne et al., 2012), after fitting a smooth curve

409 through the data for each station as a function of time, and averaging by latitude band (Masarie and Tans, 1995).

410 The annual growth rate is estimated by [Lan et al. \(2023\)](#) from atmospheric CO<sub>2</sub> concentration by taking the

411 average of the most recent December–January months corrected for the average seasonal cycle and subtracting

412 this same average one year earlier. The growth rate in units of ppm yr<sup>–1</sup> is converted to units of GtC yr<sup>–1</sup> by

413 multiplying by a factor of 2.124 GtC per ppm, assuming instantaneous mixing of CO<sub>2</sub> throughout the

414 atmosphere (Ballantyne et al., 2012; Table 1).

415 Since 2020, NOAA/GML provides estimates of atmospheric CO<sub>2</sub> concentrations with respect to a new

416 calibration scale, referred to as WMO-CO<sub>2</sub>-X2019, in line with [a recalibration agreed by the World](#)

417 Meteorological Organization (WMO) Global Atmosphere Watch (GAW) community (Hall et al., 2021). The re-

418 calibrated data were first used to estimate G<sub>ATM</sub> in the 2021 edition of the global carbon budget (Friedlingstein

419 et al., 2022a). Friedlingstein et al. (2022a) verified that the change of scales from WMO-CO<sub>2</sub>-X2007 to WMO-

420 CO<sub>2</sub>-X2019 made a negligible difference to the value of G<sub>ATM</sub> (–0.06 GtC yr<sup>–1</sup> during 2010–2019 and –0.01 GtC

421 yr<sup>–1</sup> during 1959–2019, well within the uncertainty range reported below).

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Deleted: 2021). The "X" in the scale name indicates that it is a mole fraction scale, how many micro-moles of CO<sub>2</sub> in one mole of (dry) air. The word "concentration" only loosely reflects this. The WMO-CO<sub>2</sub>-X2019 scale improves upon the earlier WMO-CO<sub>2</sub>-X2007 scale by including a broader set of standards, which contain CO<sub>2</sub> in a wider range of concentrations that span the range 250–800 ppm (versus 250–520 ppm for WMO-CO<sub>2</sub>-X2007). In addition, NOAA/GML made two minor corrections to the analytical procedure used to quantify CO<sub>2</sub> concentrations, fixing an error in the second virial coefficient of CO<sub>2</sub> and accounting for loss of a small amount of CO<sub>2</sub> to materials in the manometer during the measurement process. The difference in concentrations measured using WMO-CO<sub>2</sub>-X2019 versus WMO-CO<sub>2</sub>-X2007 is ~+0.18 ppm at 400 ppm and the observational record of atmospheric CO<sub>2</sub> concentrations have been revised accordingly. The revisions have been applied retrospectively in all cases where the calibrations were performed by NOAA/GML, thus affecting measurements made by members of the WMO-GAW programme and other regionally coordinated programmes (e.g., Integrated Carbon Observing System, ICOS). Changes to the CO<sub>2</sub> concentrations measured across these networks propagate to the global mean CO<sub>2</sub> concentrations.



1452 The uncertainty around the atmospheric growth rate is due to four main factors. First, the long-term  
 1453 reproducibility of reference gas standards (around 0.03 ppm for  $1\sigma$  from the 1980s; [Lan et al., 2023](#)). Second,  
 1454 small unexplained systematic analytical errors that may have a duration of several months to two years come  
 1455 and go. They have been simulated by randomising both the duration and the magnitude (determined from the  
 1456 existing evidence) in a Monte Carlo procedure. Third, the network composition of the marine boundary layer  
 1457 with some sites coming or going, gaps in the time series at each site, etc ([Lan et al., 2023](#)). The latter uncertainty  
 1458 was estimated by NOAA/GML with a Monte Carlo method by constructing 100 "alternative" networks (Masarie  
 1459 and Tans, 1995; NOAA/GML, 2019). The second and third uncertainties, summed in quadrature, add up to  
 1460 0.085 ppm on average ([Lan et al., 2023](#)). Fourth, the uncertainty associated with using the average CO<sub>2</sub>  
 1461 concentration from a surface network to approximate the true atmospheric average CO<sub>2</sub> concentration (mass-  
 1462 weighted, in 3 dimensions) as needed to assess the total atmospheric CO<sub>2</sub> burden. In reality, CO<sub>2</sub> variations  
 1463 measured at the stations will not exactly track changes in total atmospheric burden, with offsets in magnitude  
 1464 and phasing due to vertical and horizontal mixing. This effect must be very small on decadal and longer time  
 1465 scales, when the atmosphere can be considered well mixed. The CO<sub>2</sub> increase in the stratosphere lags the  
 1466 increase (meaning lower concentrations) that we observe in the marine boundary layer, while the continental  
 1467 boundary layer (where most of the emissions take place) leads the marine boundary layer with higher  
 1468 concentrations. These effects nearly cancel each other. In addition the growth rate is nearly the same everywhere  
 1469 (Ballantyne et al, 2012). We therefore maintain an uncertainty around the annual growth rate based on the  
 1470 multiple stations data set ranges between 0.11 and 0.72 GtC yr<sup>-1</sup>, with a mean of 0.61 GtC yr<sup>-1</sup> for 1959-1979  
 1471 and 0.17 GtC yr<sup>-1</sup> for 1980-2022, when a larger set of stations were available as provided by [Lan et al. \(2023\)](#).  
 1472 We estimate the uncertainty of the decadal averaged growth rate after 1980 at 0.02 GtC yr<sup>-1</sup> based on the  
 1473 calibration and the annual growth rate uncertainty but stretched over a 10-year interval. For years prior to 1980,  
 1474 we estimate the decadal averaged uncertainty to be 0.07 GtC yr<sup>-1</sup> based on a factor proportional to the annual  
 1475 uncertainty prior and after 1980 ( $0.02 * [0.61/0.17]$  GtC yr<sup>-1</sup>).

1476 We assign a high confidence to the annual estimates of  $G_{ATM}$  because they are based on direct measurements  
 1477 from multiple and consistent instruments and stations distributed around the world (Ballantyne et al., 2012; Hall  
 1478 et al., 2021).

1479 To estimate the total carbon accumulated in the atmosphere since 1750 or 1850, we use an atmospheric CO<sub>2</sub>  
 1480 concentration of  $278.3 \pm 3$  ppm or  $285.1 \pm 3$  ppm, respectively (Gulev et al., 2021). For the construction of the  
 1481 cumulative budget shown in Figure 3, we use the fitted estimates of CO<sub>2</sub> concentration from Joos and Spahni  
 1482 (2008) to estimate the annual atmospheric growth rate using the conversion factors shown in Table 1. The  
 1483 uncertainty of  $\pm 3$  ppm (converted to  $\pm 1\sigma$ ) is taken directly from the IPCC's AR5 assessment (Ciais et al., 2013).  
 1484 Typical uncertainties in the growth rate in atmospheric CO<sub>2</sub> concentration from ice core data are equivalent to  
 1485  $\pm 0.1$ - $0.15$  GtC yr<sup>-1</sup> as evaluated from the Law Dome data (Etheridge et al., 1996) for individual 20-year intervals  
 1486 over the period from 1850 to 1960 (Bruno and Joos, 1997).

#### 1487 2.4.2 2023 projection

1488 We provide an assessment of  $G_{ATM}$  for 2023 as the average of two methods. As in previous GCB releases, we  
 1489 use the observed monthly global atmospheric CO<sub>2</sub> concentration (GLO) through June 2023 ([Lan et al., 2023](#)),

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and ~~the~~ bias-adjusted Holt–Winters exponential smoothing with additive seasonality (Chatfield, 1978) to project to January 2024. The uncertainty is estimated from past variability using the standard deviation of the last 5 years' monthly growth rates. For the first time this year, we also use the multi-model mean and uncertainty of the 2023 GATM estimated by the ESMs prediction system (see Section 2.9). We then take the average of the Holt–Winters and ESMs GATM estimates, with their respective uncertainty combined quadratically.

Similarly, the projection of the 2023 global average CO<sub>2</sub> concentration (in ppm), is calculated as the average of the estimates from the two methods. For Holt–Winters method, it is the annual average of global concentration over the 12 months; for the ESMs, it is the observed global average CO<sub>2</sub> concentration for 2022 plus the annual increase in 2023 predicted by the ESMs multi-model mean.

## 2.5 Ocean CO<sub>2</sub> sink

### 2.5.1 Historical period 1850–2022

The reported estimate of the global ocean anthropogenic CO<sub>2</sub> sink  $S_{\text{OCEAN}}$  is derived as the average of two estimates. The first estimate is derived as the mean over an ensemble of ten global ocean biogeochemistry models (GOBMs, Table 4 and Table A2). The second estimate is obtained as the mean over an ensemble of seven surface ocean  $f\text{CO}_2$ -observation-based data-products (Table 4 and Table A3). An eighth  $f\text{CO}_2$ -product (Watson et al., 2020) is shown, but is not included in the ensemble average as it differs from the other products by adjusting the flux to a cool, salty ocean surface skin (see Appendix C.3.1 for a discussion of the Watson product). The GOBMs simulate both the natural and anthropogenic CO<sub>2</sub> cycles in the ocean. They constrain the anthropogenic air-sea CO<sub>2</sub> flux (the dominant component of  $S_{\text{OCEAN}}$ ) by the transport of carbon into the ocean interior, which is also the controlling factor of present-day ocean carbon uptake in the real world. They cover the full globe and all seasons and were recently evaluated against surface ocean carbon observations, suggesting they are suitable to estimate the annual ocean carbon sink (Hauck et al., 2020). The  $f\text{CO}_2$ -products are tightly linked to observations of  $f\text{CO}_2$  (fugacity of CO<sub>2</sub>, which equals  $p\text{CO}_2$  corrected for the non-ideal behaviour of the gas; Pfeil et al., 2013), which carry imprints of temporal and spatial variability, but are also sensitive to uncertainties in gas-exchange parameterizations and data-sparsity (Gloege et al., 2021, Hauck et al., 2023). Their asset is the assessment of the mean spatial pattern of variability and its seasonality (Hauck et al., 2020, Gloege et al. 2021, Hauck et al., 2023). We further use two diagnostic ocean models to estimate  $S_{\text{OCEAN}}$  over the industrial era (1781–1958).

The global  $f\text{CO}_2$ -based flux estimates were adjusted to remove the pre-industrial ocean source of CO<sub>2</sub> to the atmosphere of  $0.65 \pm 0.3$  GtC yr<sup>-1</sup> from river input to the ocean (Regnier et al., 2022), to satisfy our definition of  $S_{\text{OCEAN}}$  (Hauck et al., 2020). The river flux adjustment was distributed over the latitudinal bands using the regional distribution of Lacroix et al. (2020; North:  $0.14$  GtC yr<sup>-1</sup>, Tropics:  $0.42$  GtC yr<sup>-1</sup>, South:  $0.09$  GtC yr<sup>-1</sup>). Acknowledging that this distribution is based on only one model, the advantage is that a gridded field is available and the river flux adjustment can be calculated for the three latitudinal bands and the RECCAP regions (REgional Carbon Cycle Assessment and Processes (RECCAP2; Ciais et al., 2020). This data set suggests that more of the riverine outgassing is located in the tropics than in the Southern Ocean, and is thus opposed to the previously used data set of Aumont et al. (2001). Accordingly, the regional distribution is associated with a

Deleted: Tans, 2022), and

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major uncertainty, in addition to the large uncertainty around the global estimate (Crisp et al., 2022; Gruber et al., 2023). Anthropogenic perturbations of river carbon and nutrient transport to the ocean are not considered (see Section 2.10 and Appendix D.3).

We derive  $SO_{OCEAN}$  from GOBMs by using a simulation (sim A) with historical forcing of climate and atmospheric  $CO_2$ , accounting for model biases and drift from a control simulation (sim B) with constant atmospheric  $CO_2$  and normal year climate forcing. A third simulation (sim C) with historical atmospheric  $CO_2$  increase and normal year climate forcing is used to attribute the ocean sink to  $CO_2$  (sim C minus sim B) and climate (sim A minus sim C) effects. A fourth simulation (sim D; historical climate forcing and constant atmospheric  $CO_2$ ) is used to compare the change in anthropogenic carbon inventory in the interior ocean (sim A minus sim D) to the observational estimate of Gruber et al. (2019) with the same flux components (steady state and non-steady state anthropogenic carbon flux). The  $fCO_2$ -products are adjusted with respect to their original publications to represent the full ice-free ocean area, including coastal zones and marginal seas, when the area coverage is below 99%. This is done by either area filling following Fay et al. (2021) or a simple scaling approach. GOBMs and  $fCO_2$ -products fall within the observational constraints over the 1990s ( $2.2 \pm 0.7$  GtC yr<sup>-1</sup>; Ciais et al., 2013) after applying adjustments.

$SO_{OCEAN}$  is calculated as the average of the GOBM ensemble mean and the  $fCO_2$ -product ensemble mean from 1990 onwards. Prior to 1990, it is calculated as the GOBM ensemble mean plus half of the offset between GOBMs and  $fCO_2$ -products ensemble means over 1990-2001.

We assign an uncertainty of  $\pm 0.4$  GtC yr<sup>-1</sup> to the ocean sink based on a combination of random (ensemble standard deviation) and systematic uncertainties (GOBMs bias in anthropogenic carbon accumulation, previously reported uncertainties in  $fCO_2$ -products; see Appendix C.3.4). We assess a medium confidence level to the annual ocean  $CO_2$  sink and its uncertainty because it is based on multiple lines of evidence, it is consistent with ocean interior carbon estimates (Gruber et al., 2019, see Section 3.6.5) and the interannual variability in the GOBMs and data-based estimates is largely consistent and can be explained by climate variability. We refrain from assigning a high confidence because of the systematic deviation between the GOBM and  $fCO_2$ -product trends since around 2002. More details on the  $SO_{OCEAN}$  methodology can be found in Appendix C.3.

## 2.5.2 2023 Projection

The ocean  $CO_2$  sink forecast for the year 2023 is based on the annual historical (Lan et al., 2023) and our estimated 2023 atmospheric  $CO_2$  concentration growth rate, the historical and our estimated 2023 annual global fossil fuel emissions from this year's carbon budget, and the spring (March, April, May) Oceanic Niño Index (ONI) (NCEP, 2023). Using a non-linear regression approach, i.e., a feed-forward neural network, atmospheric  $CO_2$ , ONI, and the fossil fuel emissions are used as training data to best match the annual ocean  $CO_2$  sink (i.e. combined  $SO_{OCEAN}$  estimate from GOBMs and data products) from 1959 through 2022 from this year's carbon budget. Using this relationship, the 2023  $SO_{OCEAN}$  can then be estimated from the projected 2022 input data using the non-linear relationship established during the network training. To avoid overfitting, the neural network was trained with a variable number of hidden neurons (varying between 2-5) and 20% of the randomly selected training data were withheld for independent internal testing. Based on the best output performance (tested using

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the 20% withheld input data), the best performing number of neurons was selected. In a second step, we trained the network 10 times using the best number of neurons identified in step 1 and different sets of randomly selected training data. The mean of the 10 trainings is considered our best forecast, whereas the standard deviation of the 10 ensembles provides a first order estimate of the forecast uncertainty. This uncertainty is then combined with the  $S_{OCEAN}$  uncertainty ( $0.4 \text{ GtC yr}^{-1}$ ) to estimate the overall uncertainty of the [2023 projection](#). [As an additional line of evidence, we also assess the 2023 atmosphere-ocean carbon flux from the ESM prediction system \(see Section 2.9\).](#)

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## 2.6 Land CO<sub>2</sub> sink

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### 2.6.1 Historical Period [1850-2022](#)

The terrestrial land sink ( $S_{LAND}$ ) is thought to be due to the combined effects of fertilisation by rising atmospheric CO<sub>2</sub> and N inputs on plant growth, as well as the effects of climate change such as the lengthening of the growing season in northern temperate and boreal areas.  $S_{LAND}$  does not include land sinks directly resulting from land-use and land-use change (e.g., regrowth of vegetation) as these are part of the land-use flux ( $E_{LUC}$ ), although system boundaries make it difficult to attribute exactly CO<sub>2</sub> fluxes on land between  $S_{LAND}$  and  $E_{LUC}$  (Erb et al., 2013).

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$S_{LAND}$  is estimated from the multi-model mean of [20 DGVMs \(Table A1\) with an additional comparison of DGVMs with a data-driven, carbon data model framework \(CARDAMOM\) \(Bloom and Williams, 2015; Bloom et al., 2016\), see Appendix C.4](#). As described in Appendix C.4, DGVMs simulations include all climate variability and CO<sub>2</sub> effects over land. In addition to the carbon cycle represented in all DGVMs, [14](#) models also account for the nitrogen cycle and hence can include the effect of N inputs on  $S_{LAND}$ . The DGVMs estimate of  $S_{LAND}$  does not include the export of carbon to aquatic systems or its historical perturbation, which is discussed in Appendix D3. See Appendix C.4 for DGVMs evaluation and uncertainty assessment for  $S_{LAND}$ , using the International Land Model Benchmarking system (ILAMB; Collier et al., 2018). More details on the  $S_{LAND}$  methodology can be found in Appendix C.4.

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### 2.6.2 [2023](#) Projection

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Like for the ocean forecast, the land CO<sub>2</sub> sink ( $S_{LAND}$ ) forecast is based on the annual historical ([Lan et al., 2023](#)) and [our](#) estimated [2023](#) atmospheric CO<sub>2</sub> concentration, historical and [our](#) estimated [2023](#) annual global fossil fuel emissions from this year's carbon budget, and the summer (June, July, August) ONI (NCEP, 2022). All training data are again used to best match  $S_{LAND}$  from 1959 through [2022](#) from this year's carbon budget using a feed-forward neural network. To avoid overfitting, the neural network was trained with a variable number of hidden neurons (varying between 2-15), larger than for  $S_{OCEAN}$  prediction due to the stronger land carbon interannual variability. As done for  $S_{OCEAN}$ , a pre-training selects the optimal number of hidden neurons based on 20% withheld input data, and in a second step, an ensemble of 10 forecasts is produced to provide the mean forecast plus uncertainty. This uncertainty is then combined with the  $S_{LAND}$  uncertainty for [2022](#) ( $0.9 \text{ GtC yr}^{-1}$ ) to estimate the overall uncertainty of the [2023](#) projection.

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1668 **2.7 Atmospheric inversion estimate**

1669 The world-wide network of in-situ atmospheric measurements and satellite derived atmospheric CO<sub>2</sub> column  
 1670 (xCO<sub>2</sub>) observations put a strong constraint on changes in the atmospheric abundance of CO<sub>2</sub>. This is true  
 1671 globally (hence our large confidence in G<sub>ATM</sub>), but also regionally in regions with sufficient observational  
 1672 density found mostly in the extra-tropics. This allows atmospheric inversion methods to constrain the magnitude  
 1673 and location of the combined total surface CO<sub>2</sub> fluxes from all sources, including fossil and land-use change  
 1674 emissions and land and ocean CO<sub>2</sub> fluxes. The inversions assume E<sub>FOS</sub> to be well known, and they solve for the  
 1675 spatial and temporal distribution of land and ocean fluxes from the residual gradients of CO<sub>2</sub> between stations  
 1676 that are not explained by fossil fuel emissions. By design, such systems thus close the carbon balance (B<sub>IM</sub> = 0)  
 1677 and thus provide an additional perspective on the independent estimates of the ocean and land fluxes.

1678 This year's release includes [fourteen](#) inversion systems that are described in Table A4, of which thirteen are  
 1679 [included in the ensemble of inverse estimates presented in the text and figures](#). Each system is rooted in  
 1680 Bayesian inversion principles but uses different methodologies. These differences concern the selection of  
 1681 atmospheric CO<sub>2</sub> data or xCO<sub>2</sub>, and the choice of a-priori fluxes to refine. They also differ in spatial and  
 1682 temporal resolution, assumed correlation structures, and mathematical approach of the models (see references in  
 1683 Table A4 for details). Importantly, the systems use a variety of transport models, which was demonstrated to be  
 1684 a driving factor behind differences in atmospheric inversion-based flux estimates, and specifically their  
 1685 distribution across latitudinal bands (Gaubert et al., 2019; Schuh et al., 2019). [Six](#) inversion systems (CAMS-  
 1686 [FT23r1](#), CMS-flux, GONGGA, THU, [COLA](#), [GCASv2](#)) used satellite xCO<sub>2</sub> retrievals from GOSAT and/or  
 1687 OCO-2, scaled to the WMO 2019 calibration scale. [Two inversions](#) this year (CMS-Flux, [COLA](#)) used these  
 1688 xCO<sub>2</sub> datasets in addition to the in-situ observational CO<sub>2</sub> mole fraction records.

1689 The original products delivered by the inverse modellers were modified to facilitate the comparison to the other  
 1690 elements of the budget, specifically on two accounts: (1) global total fossil fuel emissions including cement  
 1691 carbonation CO<sub>2</sub> uptake, and (2) riverine CO<sub>2</sub> transport. Details are given below. We note that with these  
 1692 adjustments the inverse results no longer represent the net atmosphere-surface exchange over land/ocean areas  
 1693 as sensed by atmospheric observations. Instead, for land, they become the net uptake of CO<sub>2</sub> by vegetation and  
 1694 soils that is not exported by fluvial systems, similar to the DGVMs estimates. For oceans, they become the net  
 1695 uptake of anthropogenic CO<sub>2</sub>, similar to the GOBMs estimates.

1696 The inversion systems prescribe global fossil fuel emissions based on [e.g.](#) the GCP's Gridded Fossil Emissions  
 1697 Dataset versions [2023.1](#) (GCP-GridFED; Jones et al., [2023](#)), which are updates to GCP-GridFEDv2021  
 1698 presented by Jones et al. ([2021b](#)). GCP-[GridFEDv2023](#) scales gridded estimates of CO<sub>2</sub> emissions from  
 1699 EDGARv4.3.2 (Janssens-Maenhout et al., 2019) within national territories to match national emissions  
 1700 estimates provided by the GCB for the years 1959-[2022](#), which were compiled following the methodology  
 1701 described in Section 2.1. Small differences between the systems due to for instance regridding to the transport  
 1702 model resolution, or use of different [fossil fuel emissions](#), are adjusted in the latitudinal partitioning we present,  
 1703 to ensure agreement with the estimate of E<sub>FOS</sub> in this budget. We also note that the ocean fluxes used as prior by  
 1704 [8](#) out of [14](#) inversions are part of the suite of the ocean process model or [fCO<sub>2</sub>](#) products listed in Section 2.5.

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1723 Although these fluxes are further adjusted by the atmospheric inversions, it makes the inversion estimates of the  
1724 ocean fluxes not completely independent of  $S_{\text{OCEAN}}$  assessed here.

1725 To facilitate comparisons to the independent  $S_{\text{OCEAN}}$  and  $S_{\text{LAND}}$ , we used the same corrections for transport and  
1726 outgassing of carbon transported from land to ocean, as done for the observation-based estimates of  $S_{\text{OCEAN}}$  (see  
1727 Appendix C.3).

1728 The atmospheric inversions are evaluated using vertical profiles of atmospheric  $\text{CO}_2$  concentrations (Figure B4).  
1729 More than 30 aircraft programs over the globe, either regular programs or repeated surveys over at least 9  
1730 months (except for SH programs), have been used to assess system performance (with space-time observational  
1731 coverage sparse in the SH and tropics, and denser in NH mid-latitudes; Table A7). The ~~fourteen~~ systems are  
1732 compared to the independent aircraft  $\text{CO}_2$  measurements between 2 and 7 km above sea level between 2001 and  
1733 2022. Results are shown in Figure B4 and discussed in Appendix C.5.2. ~~One inversion was flagged for concerns~~  
1734 ~~after quality control with these observations, as well as assessment of their global growth rate. This makes the~~  
1735 ~~number of systems included in the ensemble to be  $N=13$ .~~

1736 With a relatively small ensemble of systems that ~~cover at least one full decade ( $N=9$ ), and which~~ moreover share  
1737 some a-priori fluxes used with one another, or with the process-based models, it is difficult to justify using their  
1738 mean and standard deviation as a metric for uncertainty across the ensemble. We therefore report their full range  
1739 (min-max) without their mean. More details on the atmospheric inversions methodology can be found in  
1740 Appendix C.5.

1741 **2.8 Atmospheric oxygen based estimate**

1742 Long-term atmospheric  $\text{O}_2$  and  $\text{CO}_2$  observations allow estimation of the global ocean and land carbon sinks,  
1743 due to the coupling of  $\text{O}_2$  and  $\text{CO}_2$  with distinct exchange ratios for fossil fuel emissions and land uptake, and  
1744 uncoupled  $\text{O}_2$  and  $\text{CO}_2$  ocean exchange (Keeling and Manning, 2014). The global ocean and net land carbon  
1745 sinks were calculated following methods and constants used in Keeling and Manning (2014), but modified to  
1746 also include the effective  $\text{O}_2$  source from metal refining (Battle et al., 2023), and using a value of 1.05 for the  
1747 exchange ratio of the net land sink, following Resplandy et al. (2019). Atmospheric  $\text{O}_2$  is observed as  $\delta(\text{O}_2/\text{N}_2)$   
1748 and combined with  $\text{CO}_2$  mole fraction observations into Atmospheric Potential Oxygen (APO, Stephens et al.,  
1749 1998). The APO observations from 1990 to 2022 were taken from a weighted average of flask records from the  
1750 three stations in the Scripps  $\text{O}_2$  program network (Alert, Canada (ALT), La Jolla, California (LJO), and Cape  
1751 Grim, Australia (CGO), weighted per Keeling and Manning (2020). Observed  $\text{CO}_2$  was taken from the globally  
1752 averaged marine surface annual mean growth rate from the NOAA/ESRL Global Greenhouse Gas Reference  
1753 Network (Lan et al., 2023). The  $\text{O}_2$  source from ocean warming is based on ocean heat content from updated  
1754 data from NOAA/NCEI (Levitus et al., 2012). The effective  $\text{O}_2$  source from metal refining is based on  
1755 production data from Bray (2020), Flanagan (2021), and Tuck (2022). Uncertainty was determined through a  
1756 Monte Carlo approach with 5,000 iterations, using uncertainties prescribed in Keeling and Manning (2014),  
1757 including observational uncertainties from Keeling et al. (2007) and autoregressive errors in fossil fuel  
1758 emissions (Ballantyne et al., 2015). The reported uncertainty is one standard deviation of the ensemble.

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## 2.9 Earth System Models estimate

Reconstructions and predictions from decadal prediction systems based on Earth system models (ESMs) provide a novel line of evidence in assessing the atmosphere-land and atmosphere-ocean carbon fluxes in the past decades and predicting their changes for the current year. The decadal prediction systems based on ESMs used here consist of three sets of simulations: (i) uninitialized freely evolving historical simulations (1850-2014); (ii) assimilation reconstruction incorporating observational data into the model (1980-2022); (iii) initialized prediction simulations for the 1981-2023 period, starting every year from initial states obtained from the above assimilation simulations. The assimilations are designed to reconstruct the actual evolution of the Earth system by assimilating essential fields from data products. The assimilations' states, which are expected to be close to observations, are used to start the initialized prediction simulations used for the current year (2023) global carbon budget. Similar initialized prediction simulations starting every year (Nov. 1st or Jan. 1st) over the 1981-2022 period (i.e., hindcasts) are also performed for predictive skill quantification and for bias correction. More details on the illustration of a decadal prediction system based on an ESM can refer to Figure 1 of Li et al. (2023).

By assimilating physical atmospheric and oceanic data products into the ESMs, the models are able to reproduce the historical variations of the atmosphere-sea CO<sub>2</sub> fluxes, atmosphere-land CO<sub>2</sub> fluxes, and atmospheric CO<sub>2</sub> growth rate (Li et al., 2016, 2019; Lovenduski et al., 2019a,b; Ilyina et al., 2021; Li et al., 2023). Furthermore, the ESM-based predictions have proven their skill in predicting the air-sea CO<sub>2</sub> fluxes for up to 6 years, the air-land CO<sub>2</sub> fluxes and atmospheric CO<sub>2</sub> growth for 2 years (Lovenduski et al., 2019a,b; Ilyina et al., 2021; Li et al., 2023). The reconstructions from the fully coupled model simulations ensure a closed budget within the Earth system, i.e., no budget imbalance term.

Four ESMs, i.e., CanESM5 (Swart et al., 2019; Sospedra-Alfonso et al., 2021), IPSL-CM6A-CO2-LR (Boucher et al., 2020), MIROC-ES2L (Watanabe et al., 2020), and MPI-ESM1-2-LR (Mauritsen et al., 2019; Li et al., 2023), have performed the set of prediction simulations. Each ESM uses a different assimilation method and combination of data products incorporated in the system, more details on the models configuration can be found in Table 4. The ESMs use external forcings from the Coupled Model Intercomparison Project Phase 6 (CMIP6) historical (1980-2014) plus SSP2-4.5 baseline and CovidMIP two year blip scenario (2015-2023) (Eyring et al., 2016; Jones et al., 2021a). The CO<sub>2</sub> emissions forcing from 2015-2023 are substituted by GCB-GridFED (v2023.1, Jones et al., 2023) to provide a more realistic forcing. Reconstructions of atmosphere-ocean CO<sub>2</sub> fluxes (S<sub>ocean</sub>) and atmosphere-land CO<sub>2</sub> fluxes (S<sub>land-ELUC</sub>) for the time period from 1980-2022 are assessed here. Predictions of the atmosphere-ocean CO<sub>2</sub> flux, atmosphere-land CO<sub>2</sub> flux, and atmospheric CO<sub>2</sub> growth for 2023 are calculated based on the predictions at a lead time of 1 year. The predictions are bias-corrected using the 1985-2014 climatology mean of GCB2022 (Friedlingstein et al., 2022), more details on methods can be found in Boer et al. (2016) and Li et al. (2023). The ensemble size of initialized prediction simulations is 10, and the ensemble mean for each individual model is used here. The ESMs are used here to support the assessment of S<sub>ocean</sub> and net atmosphere-land CO<sub>2</sub> flux (S<sub>land</sub> - E<sub>luc</sub>) over the 1980-2022 period, and to provide an estimate of the 2023 projection of G<sub>atm</sub>.

## 1800 2.10 Processes not included in the global carbon budget

1801 The contribution of anthropogenic CO and CH<sub>4</sub> to the global carbon budget is not fully accounted for in Eq. (1)  
1802 and is described in Appendix D1. The contributions to CO<sub>2</sub> emissions of decomposition of carbonates not  
1803 accounted for is described in Appendix D2. The contribution of anthropogenic changes in river fluxes is  
1804 conceptually included in Eq. (1) in SO<sub>CEAN</sub> and in S<sub>LAND</sub>, but it is not represented in the process models used to  
1805 quantify these fluxes. This effect is discussed in Appendix D3. Similarly, the loss of additional sink capacity  
1806 from reduced forest cover is missing in the combination of approaches used here to estimate both land fluxes  
1807 (E<sub>LUC</sub> and S<sub>LAND</sub>) and its potential effect is discussed and quantified in Appendix D4.

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## 1808 3 Results

1809 For each component of the global carbon budget, we present results for three different time periods: the full  
1810 historical period, from 1850 to 2022, the decades in which we have atmospheric concentration records from  
1811 Mauna Loa (1960-2022), a specific focus on last year (2022), and the projection for the current year (2023).  
1812 Subsequently, we assess the estimates of the budget components of the last decades against the top-down  
1813 constraints from inverse modelling of atmospheric observations, the land/ocean partitioning derived from the  
1814 atmospheric O<sub>2</sub> measurements, and the budget components estimates from the ESMs assimilation simulations.  
1815 Atmospheric inversions further allow for an assessment of the budget components with a regional breakdown of  
1816 land and ocean sinks.

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### 1817 3.1 Fossil CO<sub>2</sub> Emissions

#### 1818 3.1.1 Historical period 1850-2022

1819 Cumulative fossil CO<sub>2</sub> emissions for 1850-2022 were 477 ± 25 GtC, including the cement carbonation sink  
1820 (Figure 3, Table 8, with all cumulative numbers rounded to the nearest 5GtC). In this period, 46% of global  
1821 fossil CO<sub>2</sub> emissions came from coal, 35% from oil, 15% from natural gas, 3% from decomposition of  
1822 carbonates, and 1% from flaring. In 1850, the UK stood for 62% of global fossil CO<sub>2</sub> emissions. In 1891 the  
1823 combined cumulative emissions of the current members of the European Union reached and subsequently  
1824 surpassed the level of the UK. Since 1917 US cumulative emissions have been the largest. Over the entire  
1825 period 1850-2022, US cumulative emissions amounted to 115GtC (24% of world total), the EU's to 80 GtC  
1826 (17%), and China's to 70 GtC (15%).

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1827 In addition to the estimates of fossil CO<sub>2</sub> emissions that we provide here (see Methods), there are three global  
1828 datasets with long time series that include all sources of fossil CO<sub>2</sub> emissions: CDIAC-FF (Gilfillan and  
1829 Marland, 2021), CEDS version v\_2021\_04\_21 (Hoesly et al., 2018; O'Rourke et al., 2021) and PRIMAP-hist  
1830 version 2.4.2 (Gütschow et al., 2016; Gütschow and Pflüger, 2023), although these datasets are not entirely  
1831 independent from each other (Andrew, 2020a). CDIAC-FF has the lowest cumulative emissions over 1750-2018  
1832 at 440 GtC, GCP has 444 GtC, CEDS 445 GtC, PRIMAP-hist TP 453 GtC, and PRIMAP-hist CR 452 GtC.  
1833 CDIAC-FF excludes emissions from lime production, CEDS has higher emissions from international shipping  
1834 in recent years, while PRIMAP-hist has higher fugitive emissions than the other datasets. However, in general  
1835 these four datasets are in relative agreement as to total historical global emissions of fossil CO<sub>2</sub>.

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### 3.1.2 Recent period 1960-2022

Global fossil CO<sub>2</sub> emissions, E<sub>FOS</sub> (including the cement carbonation sink), have increased every decade from an average of  $3.0 \pm 0.2$  GtC yr<sup>-1</sup> for the decade of the 1960s to an average of  $9.6 \pm 0.5$  GtC yr<sup>-1</sup> during 2013-2022 (Table 7, Figure 2 and Figure 5). The growth rate in these emissions decreased between the 1960s and the 1990s, from 4.3% yr<sup>-1</sup> in the 1960s (1960-1969), 3.2% yr<sup>-1</sup> in the 1970s (1970-1979), 1.6% yr<sup>-1</sup> in the 1980s (1980-1989), to 1.0% yr<sup>-1</sup> in the 1990s (1990-1999). After this period, the growth rate began increasing again in the 2000s at an average growth rate of 2.8% yr<sup>-1</sup>, decreasing to 0.5% yr<sup>-1</sup> for the last decade (2013-2022). China's emissions increased by +1.6% yr<sup>-1</sup> on average over the last 10 years dominating the global trend, and India's emissions increased by +3.5% yr<sup>-1</sup>, while emissions decreased in EU27 by -1.7% yr<sup>-1</sup>, and in the USA by -1.0% yr<sup>-1</sup>. Figure 6 illustrates the spatial distribution of fossil fuel emissions for the 2013-2022 period.

E<sub>FOS</sub> reported here includes the uptake of CO<sub>2</sub> by cement via carbonation which has increased with increasing stocks of cement products, from an average of 20 MtC yr<sup>-1</sup> (0.02 GtC yr<sup>-1</sup>) in the 1960s to an average of 206 MtC yr<sup>-1</sup> (0.21 GtC yr<sup>-1</sup>) during 2013-2022 (Figure 5).

### 3.1.3 Final year 2022

Global fossil CO<sub>2</sub> emissions were slightly higher, 0.85%, in 2022 than in 2021, with an increase of less than 0.1 GtC to reach  $9.9 \pm 0.5$  GtC (including the 0.2 GtC cement carbonation sink) in 2022 (Figure 5), distributed among coal (41%), oil (32%), natural gas (21%), cement (4%), flaring (1%), and others (1%). Compared to the previous year, 2022 emissions from coal and oil increased by 1.6% and 3.3% respectively, while emissions from gas and cement respectively decreased by 2.2% and 5.7%. All growth rates presented are adjusted for the leap year, unless stated otherwise.

In 2022, the largest absolute contributions to global fossil CO<sub>2</sub> emissions were from China (31%), the USA (14%), India (8%), and the EU27 (7%). These four regions account for 59% of global fossil CO<sub>2</sub> emissions, while the rest of the world contributed 41%, including international aviation and marine bunker fuels (2.6% of the total). Growth rates for these countries from 2021 to 2022 were 0.9% (China), 1% (USA), -1.9% (EU27), and 5.8% (India), with +0.6% for the rest of the world. The per-capita fossil CO<sub>2</sub> emissions in 2022 were 1.3 tC person<sup>-1</sup> yr<sup>-1</sup> for the globe, and were 4.1 (USA), 2.2 (China), 1.7 (EU27) and 0.5 (India) tC person<sup>-1</sup> yr<sup>-1</sup> for the four highest emitters (Figure 5).

### 3.1.4 Year 2023 Projection

Globally, we estimate that global fossil CO<sub>2</sub> emissions (including cement carbonation) will grow by 1.2% in 2023 (0.2% to 2.3%) to 10.0 GtC (36.8 GtCO<sub>2</sub>), exceeding the pre-COVID19 2019 emission levels of 9.9 GtC (36.3 GtCO<sub>2</sub>). Global increase in 2023 emissions per fuel types are projected to be +1.1% (range -0.2% to 2.4%) for coal, +1.8% (range 0.8% to 2.9%) for oil, +0.3% (range -0.6% to 1.3%) for natural gas, and -1.8% (range 0.2% to 3.4%) for cement.

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Deleted: 2021...022, the largest absolute contributions to global fossil CO<sub>2</sub> emissions were from China (31%), the USA (14%), India (8%), and the EU27 (8%), and India (...%). These four regions account for 59% of global fossil CO<sub>2</sub> emissions, while the rest of the world contributed 41%, including international aviation and marine bunker fuels (2.8...% of the total). Growth rates for these countries from 2020 to ...021 to 2022 were 3.5...9% (China), 6.2...% 6.8...1.9% (EU27), and 11.1...8% (India), with +4.5...6% for the rest of the world. The per-capita fossil CO<sub>2</sub> emissions in 2021...022 were 1.3 tC person<sup>-1</sup> yr<sup>-1</sup> for the globe, and 4.0... (USA), 2.2 (China), 1.7 (EU27) and 0.5 (India) tC person<sup>-1</sup> yr<sup>-1</sup> for the four highest emitting countries

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For China, projected fossil emissions in 2023 are expected to increase by 4% (range 1.9% to 6.2%) compared with 2022 emissions, bringing 2023 emissions for China around 3.2 GtC yr<sup>-1</sup> (11.9 GtCO<sub>2</sub> yr<sup>-1</sup>). Changes in fuel specific projections for China are 3.5% for coal, 7.7% for oil, 6.4% natural gas, and 0.2% for cement.

For the USA, the Energy Information Administration (EIA) emissions projection for 2023 combined with cement clinker data from USGS gives an decrease of 3.4% (range -5.9% to -0.9%) compared to 2022, bringing USA 2023 emissions to around 1.3 GtC yr<sup>-1</sup> (4.9 GtCO<sub>2</sub> yr<sup>-1</sup>). This is based on separate projections for coal -19.9%, oil -0.7%, natural gas +1.7%, and cement +3.2%.

For the European Union, our projection for 2023 is for a decrease of 7.1% (range -9.6% to -4.6%) over 2022, with 2023 emissions around 0.7 GtC yr<sup>-1</sup> (2.6 GtCO<sub>2</sub> yr<sup>-1</sup>). This is based on separate projections for coal of -19.6%, oil -0.9%, natural gas -6.6%, and cement unchanged.

For India, our projection for 2023 is an increase of 8% (range of 7.9% to 8.0%) over 2022, with 2023 emissions around 0.8 GtC yr<sup>-1</sup> (3.1 GtCO<sub>2</sub> yr<sup>-1</sup>). This is based on separate projections for coal of +9.2%, oil +5.2%, natural gas +4.4%, and cement +8.1%.

For the rest of the world, the expected growth rate for 2023 is 0.9% (range -0.8% to 2.6%) with 2023 emissions around 4.2 GtC yr<sup>-1</sup> (15.2 GtCO<sub>2</sub> yr<sup>-1</sup>). The fuel-specific projected 2023 growth rates for the rest of the world are: +1% for coal, +1.5% for oil, +0.3% for natural gas, +2.6% for cement.

## 3.2 Emissions from Land Use Changes

### 3.2.1 Historical period 1850-2022

Cumulative CO<sub>2</sub> emissions from land-use changes (ELUC) for 1850-2022 were 220 ± 65 GtC (Table 8; Figure 3; Figure 15). The cumulative emissions from ELUC show a large spread among individual estimates of 150 GtC (H&C2023), 290 GtC (BLUE), and 215 GtC (OSCAR) for the three bookkeeping models and a similar wide estimate of 210 ± 65 GtC for the DGVMs (all cumulative numbers are rounded to the nearest 5 GtC). These estimates are broadly consistent with indirect constraints from vegetation biomass observations, giving cumulative emissions of 155 ± 50 GtC over the 1901-2012 period (Li et al., 2017). However, given the large spread, a best estimate is difficult to ascertain.

### 3.2.2 Recent period 1960-2022

In contrast to growing fossil emissions, CO<sub>2</sub> emissions from land-use, land-use change, and forestry remained relatively constant over the 1960-1999 period. Since the 1990s they have shown a slight decrease of about 0.1 GtC per decade, reaching 1.3 ± 0.7 GtC yr<sup>-1</sup> for the 2013-2022 period (Table 7), but with large spread across estimates (Table 5, Figure 7). Different from the bookkeeping average, the DGVMs average grows slightly larger over the 1970-2022 period and shows no sign of decreasing emissions in the recent decades (Table 5, Figure 7). This is, however, expected as DGVM-based estimates include the loss of additional sink capacity, which grows with time, while the bookkeeping estimates do not (Appendix D4).

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We separate net  $E_{LUC}$  into five component fluxes to gain further insight into the drivers of net emissions: deforestation, forest (re-)growth, wood harvest and other forest management, peat drainage and peat fires, and all other transitions (Figure 7c; Sec. C.2.1). We further decompose the deforestation and the forest (re-)growth term into contributions from shifting cultivation vs permanent forest cover changes (Figure 7d). Averaged over the 2013-2022 period and over the three bookkeeping estimates, fluxes from deforestation amount to  $1.9 [1.5 \text{ to } 2.4] \text{ GtC yr}^{-1}$  (Table 5), of which  $1.1 [1.0, 1.2] \text{ GtC yr}^{-1}$  are from permanent deforestation. Fluxes from forest (re-)growth amount to  $-1.3 [-1.5, -0.9] \text{ GtC yr}^{-1}$  (Table 5), of which  $-0.5 [-0.8 \text{ to } -0.2] \text{ GtC yr}^{-1}$  are from re/afforestation and the remainder from forest regrowth in shifting cultivation cycles. Emissions from wood harvest and other forest management ( $0.2 [0.0, 0.6] \text{ GtC yr}^{-1}$ ), peat drainage and peat fires ( $0.3 [0.3, 0.3] \text{ GtC yr}^{-1}$ ) and the net flux from other transitions ( $0.1 [0.0, 0.3] \text{ GtC yr}^{-1}$ ) are substantially less important globally (Table 5). However, the small net flux from wood harvest and other forest management contains substantial gross fluxes that largely compensate each other (see Figure B7):  $1.3 [0.9, 2.0] \text{ GtC yr}^{-1}$  emissions result from the decomposition of slash and the decay of wood products and  $-1.1 [-1.3, -0.8] \text{ GtC yr}^{-1}$  removals result from regrowth after wood harvesting. This split into component fluxes clarifies the potentials for emission reduction and carbon dioxide removal: the emissions from permanent deforestation - the largest of our component fluxes - could be halted (largely) without compromising carbon uptake by forests, contributing substantially to emissions reduction. By contrast, reducing wood harvesting would have limited potential to reduce emissions as it would be associated with less forest regrowth; removals and emissions cannot be decoupled here on long timescales. A similar conclusion applies to removals and emissions from shifting cultivation, which we have therefore separated out. Carbon Dioxide Removal (CDR) in forests could instead be increased by permanently increasing the forest cover through re/afforestation. Our estimate of about  $-0.5 [-0.8, -0.2] \text{ GtC yr}^{-1}$  (of which about two thirds are located in non-Annex-I countries, in particular in China) removed on average each year during 2013-2022 by re/afforestation is very similar to independent estimates that were derived from NGHGs for 2022. Re/afforestation constitutes the vast majority of all current CDR (Powis et al., 2023). Though they cannot be compared directly to annual fluxes from the atmosphere, CDR through transfers between non-atmospheric reservoirs such as in durable HWP, biochar or BECCS comprise much smaller amounts of carbon.  $61 \text{ MtC yr}^{-1}$  have been estimated to be transferred to HWP in 2022, and BECCS projects have been estimated to store  $0.5 \text{ MtC yr}^{-1}$  in geological projects worldwide (Powis et al., 2023). "Blue carbon", i.e. coastal wetland management such as restoration of mangrove forests, saltmarshes and seagrass meadows, though at the interface of land and ocean carbon fluxes, are counted towards the land-use sector as well. Currently, bookkeeping models do not include blue carbon; however, current CDR deployment in coastal wetlands is small globally.

The small declining trend of  $E_{LUC}$  over the last three decades is a result of total deforestation emissions showing no clear trend, while forest regrowth has provided steadily increasing removals. Since the processes behind gross removals, foremost forest regrowth and soil recovery, are all slow, while gross emissions include a large instantaneous component, short-term changes in land-use dynamics, such as a temporary decrease in deforestation, influences gross emissions dynamics more than gross removals dynamics, which rather are a response to longer-term dynamics. Component fluxes often differ more across the three bookkeeping estimates than the net flux, which is expected due to different process representation; in particular, treatment of shifting cultivation, which increases both gross emissions and removals, differs across models, but also net and gross

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wood harvest fluxes show high uncertainty. By contrast, models agree relatively well for emissions from permanent deforestation emissions and removals by re/afforestation.

Overall, highest land-use emissions occur in the tropical regions of all three continents. The top three emitters (both cumulatively 1959-2022 and on average over 2013-2022) are Brazil (in particular the Amazon Arc of Deforestation), Indonesia and the Democratic Republic of the Congo, with these 3 countries contributing 0.7 GtC yr<sup>-1</sup> or 55% of the global net land-use emissions (average over 2013-2022) (Figure 6b). This is related to massive expansion of cropland, particularly in the last few decades in Latin America, Southeast Asia, and sub-Saharan Africa (Hong et al., 2021), to a substantial part for export of agricultural products (Pendrill et al., 2019). Emission intensity is high in many tropical countries, particularly of Southeast Asia, due to high rates of land conversion in regions of carbon-dense and often still pristine, undegraded natural forests (Hong et al., 2021). Emissions are further increased by peat fires in equatorial Asia (GFED4s, van der Werf et al., 2017). Uptake due to land-use change occurs, particularly in Europe, partly related to expanding forest area as a consequence of the forest transition in the 19<sup>th</sup> and 20<sup>th</sup> century and subsequent regrowth of forest (Figure 6b) (Mather 2001; McGrath et al., 2015).

While the mentioned patterns are robust and supported by independent literature, we acknowledge that model spread is substantially larger on regional than global levels, as has been shown for bookkeeping models (Bastos et al., 2021) as well as DGVMs (Obermeier et al., 2021). Assessments for individual regions will be performed as part of REgional Carbon Cycle Assessment and Processes (RECCAP2; Ciais et al., 2020) or already exist for selected regions (e.g., for Europe by Petrescu et al., 2020, for Brazil by Rosan et al., 2021, for 8 selected countries/regions in comparison to inventory data by Schwingshackl et al., 2022).

National GHG inventory data (NGHGI) under the LULUCF sector or data submitted by countries to FAOSTAT differ from the global models' definition of E<sub>LUC</sub>. In the NGHGI reporting, the natural fluxes (S<sub>LAND</sub>) are counted towards E<sub>LUC</sub> when they occur on managed land (Grassi et al., 2018). In order to compare our results to the NGHGI approach, we perform a translation of our E<sub>LUC</sub> estimates by subtracting S<sub>LAND</sub> in managed forest from the DGVMs simulations (following Grassi et al., 2021) from the bookkeeping E<sub>LUC</sub> estimate (see Appendix C.2.3). For the 2013-2022 period, we estimate that 2.0 GtC yr<sup>-1</sup> of S<sub>LAND</sub> occurred in managed forests. Subtracting this value from E<sub>LUC</sub> changes E<sub>LUC</sub> from being a source of 1.3 GtC yr<sup>-1</sup> to a sink of 0.8 GtC yr<sup>-1</sup>, very similar to the NGHGI estimate that yields a sink of 0.7 GtC yr<sup>-1</sup> (Table 9). The translation approach has been shown to be generally applicable also on country-level (Grassi et al., 2023; Schwingshackl et al., 2022). Country-level analysis suggests, e.g., that the bookkeeping method estimates higher deforestation emissions than the national report in Indonesia, but less CO<sub>2</sub> removal by afforestation than the national report in China. The fraction of the natural CO<sub>2</sub> sinks that the NGHGI estimates include differs substantially across countries, related to varying proportions of managed vs. total forest areas (Schwingshackl et al., 2022). By comparing E<sub>LUC</sub> and NGHGI on the basis of the component fluxes used above, we find that our estimates reproduce very closely the NGHGI estimates for emissions from permanent deforestation (1.1 GtC yr<sup>-1</sup> averaged over 2013-2022). Forest fluxes, that is, (re-)growth from re/afforestation plus the net flux from wood harvesting and other forest management, constitute a large sink in the NGHGI (-1.9 GtC yr<sup>-1</sup> averaged over 2013-2022), since they also include S<sub>LAND</sub> in managed forests. Summing up the bookkeeping estimates of (re-)growth from re/afforestation and the net flux from wood harvesting and other forest management and adding S<sub>LAND</sub> in managed forests yields

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a flux of -2.3 GtC yr<sup>-1</sup> (averaged over 2013-2022), which compares well with the NGHGI estimate. Emissions from organic soils in NGHGI are similar to the estimates based on the bookkeeping approach and the external peat drainage and burning datasets. The net flux from other transitions is small in both NGHGI and bookkeeping estimates, but a difference in sign (small source in bookkeeping estimates, small sink in NGHGI) creates a notable difference between NGHGI and bookkeeping estimates. Though estimates between NGHGI, FAOSTAT, and the translated budget estimates still differ in value and need further analysis, the approach suggested by Grassi et al. (2023), which we adopt here, provides a feasible way to relate the global models' and NGHGI approach to each other, and thus link the anthropogenic carbon budget estimates of land CO<sub>2</sub> fluxes directly to the Global Stocktake, as part of UNFCCC Paris Agreement.

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### 3.2.3 Final year 2022

The global CO<sub>2</sub> emissions from land-use change are estimated as  $1.2 \pm 0.7$  GtC in 2022, similar to the 2020 and 2021 estimates. However, confidence in the annual change remains low. Effects of the COVID-19 pandemic on land-use change have turned out to be country-specific as global market mechanisms, national economics and changes in household income all could act to curb or enhance deforestation (Wunder et al., 2021). Concerns about enhanced deforestation due to weakened environmental protection and monitoring in tropical countries (Brancalion et al., 2020; Vale et al., 2021) have been confirmed only for some countries (Cespedes et al., 2023). For example, a recent study suggests slightly increased deforestation rates for the Democratic Republic of Congo linked in particular to post-pandemic economic recovery in the mining sector, while deforestation trends in Brazil seem to have been unaffected. Land use dynamics may be further altered by the Russian invasion of Ukraine, but scientific evidence related to international dependencies (like a shift to tropical palm oil to alleviate dependencies on sunflower oil) so far is very limited and recent changes will not be reflected by the land-use forcing applied in the global models. High food prices, which preceded but were exacerbated by the war (FAO, 2022), are generally linked to higher deforestation (Angelsen and Kaimowitz, 1999). A new wave of cropland abandonment in the conflict region may increase the substantial Eastern European carbon sink due to land-use changes, but sanctions being placed on trade may also incentivise domestic agricultural production, thus leading to recultivation of abandoned areas in Russia (Winkler et al., 2023).

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### 3.2.4 Year 2023 Projection

In Indonesia, peat fire emissions are below average (12 Tg C through September 29 2023) despite El Niño conditions, which in general lead to more fires. Tropical deforestation and degradation fires in Indonesia are around average (13 Tg C through September 29 2023), but higher than in the previous year, which had a relatively wet dry season (GFED4.1s, van der Werf et al., 2017; see also [https://www.geo.vu.nl/~gwerf/GFED/GFED4/tables/GFED4.1s\\_C.txt](https://www.geo.vu.nl/~gwerf/GFED/GFED4/tables/GFED4.1s_C.txt)). In South America, emissions from tropical deforestation and degradation fires are among the lowest over the last decades (64 Tg C through September 29 2023). Effects of the El Niño in the Amazon, such as droughts, are not expected before 2024. Disentangling the degree to which interannual variability in rainfall patterns and stronger environmental protection measures in both Indonesia after their 2015 high fire season and in Brazil after the change in government in Brazil play a role in this is an important research topic. Cumulative fire emission estimates

through September 29 2023 are 155 Tg C for global deforestation and degradation fires and 12 Tg C for peatland fires in Indonesia ([https://www.geo.vu.nl/~gwerf/GFED/GFED4/tables/GFED4.1s\\_C.txt](https://www.geo.vu.nl/~gwerf/GFED/GFED4/tables/GFED4.1s_C.txt)).

Based on these estimates, we expect  $E_{LUC}$  emissions of around 1.1 GtC (4.1 GtCO<sub>2</sub>) in 2023. Our preliminary estimate of  $E_{LUC}$  for 2023 is substantially lower than the 2013-2022 average, which saw years of anomalously dry conditions in Indonesia and high deforestation fires in South America (Friedlingstein et al., 2022b). Note that although our extrapolation includes tropical deforestation and degradation fires, degradation attributable to selective logging, edge-effects or fragmentation is not captured. Further, deforestation and fires in deforestation zones may become more disconnected, partly due to changes in legislation in some regions. For example, Van Wees et al. (2021) found that the contribution from fires to forest loss decreased in the Amazon and in Indonesia over the period of 2003-2018.

### 3.3 CDR not based on vegetation

Besides the CDR through land-use (Sec. 3.2), the atmosphere to geosphere flux of carbon resulting from carbon dioxide removal (CDR) activity is currently 0.003 MtC/yr, with 0.002 MtC/yr of DACCS and 0.001 MtC/yr of enhanced weathering projects. This represents an offset of about 0.03% of current fossil fuel emissions.

### 3.4 Total anthropogenic emissions

Cumulative anthropogenic CO<sub>2</sub> emissions for 1850-2022 totalled  $695 \pm 70$  GtC ( $2550 \pm 260$  GtCO<sub>2</sub>), of which 70% (485 GtC) occurred since 1960 and 33% (235 GtC) since 2000 (Table 7 and 8). Total anthropogenic emissions more than doubled over the last 60 years, from  $4.6 \pm 0.7$  GtC yr<sup>-1</sup> for the decade of the 1960s to an average of  $10.9 \pm 0.8$  GtC yr<sup>-1</sup> during 2013-2022, and reaching  $11.1 \pm 0.9$  GtC ( $40.7 \pm 3.3$  GtCO<sub>2</sub>) in 2022. For 2023, we project global total anthropogenic CO<sub>2</sub> emissions from fossil and land use changes to be also around 11.2 GtC (40.9 GtCO<sub>2</sub>). All values here include the cement carbonation sink (currently about 0.2 GtC yr<sup>-1</sup>).

During the historical period 1850-2022, 31% of historical emissions were from land use change and 69% from fossil emissions. However, fossil emissions have grown significantly since 1960 while land use changes have not, and consequently the contributions of land use change to total anthropogenic emissions were smaller during recent periods (18% during the period 1960-2022 and down to 12% over the 2013-2022 period).

### 3.5 Atmospheric CO<sub>2</sub>

#### 3.5.1 Historical period 1850-2022

Atmospheric CO<sub>2</sub> concentration was approximately 278 parts per million (ppm) in 1750, reaching 300 ppm in the 1910s, 350 ppm in the late 1980s, and reaching  $417.07 \pm 0.1$  ppm in 2022 (Lan et al., 2023; Figure 1). The mass of carbon in the atmosphere increased by 48% from 590 GtC in 1750 to 886 GtC in 2022. Current CO<sub>2</sub> concentrations in the atmosphere are unprecedented in the last 2 million years and the current rate of atmospheric CO<sub>2</sub> increase is at least 10 times faster than at any other time during the last 800,000 years (Canadell et al., 2021).

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### 3.5.2 Recent period 1960-2022

The growth rate in atmospheric CO<sub>2</sub> level increased from  $1.7 \pm 0.07$  GtC yr<sup>-1</sup> in the 1960s to  $5.2 \pm 0.02$  GtC yr<sup>-1</sup> during 2013-2022 with important decadal variations (Table 7, Figure 3 and Figure 4). During the last decade (2013-2022), the growth rate in atmospheric CO<sub>2</sub> concentration continued to increase, albeit with large interannual variability (Figure 4).

The airborne fraction (AF), defined as the ratio of atmospheric CO<sub>2</sub> growth rate to total anthropogenic emissions:

$$AF = G_{ATM} / (E_{FOS} + E_{LUC}) \quad (2)$$

provides a diagnostic of the relative strength of the land and ocean carbon sinks in removing part of the anthropogenic CO<sub>2</sub> perturbation. The evolution of AF over the last 60 years shows no significant trend, remaining at around 44%, albeit showing a large interannual and decadal variability driven by the year-to-year variability in G<sub>ATM</sub> (Figure 9). The observed stability of the airborne fraction over the 1960-2020 period indicates that the ocean and land CO<sub>2</sub> sinks have been removing on average about 56% of the anthropogenic emissions (see Sections 3.6.2 and 3.7.2).

### 3.5.3 Final year 2022

The growth rate in atmospheric CO<sub>2</sub> concentration was  $4.6 \pm 0.2$  GtC ( $2.18 \pm 0.08$  ppm) in 2022 (Figure 4; Lan et al., 2023), below the 2021 growth rate ( $5.2 \pm 0.2$  GtC), or the 2013-2022 average ( $5.2 \pm 0.02$  GtC).

### 3.5.4 Year 2023 Projection

The 2023 growth in atmospheric CO<sub>2</sub> concentration (G<sub>ATM</sub>) is projected to be about 4.0 GtC (1.89 ppm). This is the average of the Holt-Winters method (3.7 GtC, 1.73 ppm) and ESMs the multi-model mean (4.4 GtC, 2.05 ppm). The 2023 atmospheric CO<sub>2</sub> concentration, averaged over the year, is expected to reach the level of 419.2 ppm, 51% over the pre-industrial level.

## 3.6 Ocean Sink

### 3.6.1 Historical period 1850-2022

Cumulated since 1850, the ocean sink adds up to  $180 \pm 35$  GtC, with more than two thirds of this amount (125 GtC) being taken up by the global ocean since 1960. Over the historical period, the ocean sink increased in pace with the anthropogenic emissions exponential increase (Figure 3). Since 1850, the ocean has removed 26% of total anthropogenic emissions.

### 3.6.2 Recent period 1960-2022

The ocean CO<sub>2</sub> sink increased from  $1.1 \pm 0.4$  GtC yr<sup>-1</sup> in the 1960s to  $2.8 \pm 0.4$  GtC yr<sup>-1</sup> during 2013-2022 (Table 7), with interannual variations of the order of a few tenths of GtC yr<sup>-1</sup> (Figure 10). The ocean-borne fraction (S<sub>OCEAN</sub>/(E<sub>FOS</sub>+E<sub>LUC</sub>)) has been remarkably constant around 25% on average (Figure 9c), with variations

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around this mean, illustrating the decadal variability of the ocean carbon sink. So far, there is no indication of a decrease in the ocean-borne fraction from 1960 to 2022. The increase of the ocean sink is primarily driven by the increased atmospheric CO<sub>2</sub> concentration, with the strongest CO<sub>2</sub> induced signal in the North Atlantic and the Southern Ocean (Figure 11a). The effect of climate change is much weaker, reducing the ocean sink globally by  $0.16 \pm 0.04$  GtC yr<sup>-1</sup> (-6.7% of SO<sub>CEAN</sub>) during 2013-2022 (all models simulate a weakening of the ocean sink by climate change, range -4.3 to -10.3%), and does not show clear spatial patterns across the GOBMs ensemble (Figure 11b). This is the combined effect of change and variability in all atmospheric forcing fields, previously attributed, in one model, to wind and temperature changes (LeQuéré et al., 2010).

The global net air-sea CO<sub>2</sub> flux is a residual of large natural and anthropogenic CO<sub>2</sub> fluxes into and out of the ocean with distinct regional and seasonal variations (Figure 6 and B1). Natural fluxes dominate on regional scales, but largely cancel out when integrated globally (Gruber et al., 2009). Mid-latitudes in all basins and the high-latitude North Atlantic dominate the ocean CO<sub>2</sub> uptake where low temperatures and high wind speeds facilitate CO<sub>2</sub> uptake at the surface (Takahashi et al., 2009). In these regions, formation of mode, intermediate and deep-water masses transport anthropogenic carbon into the ocean interior, thus allowing for continued CO<sub>2</sub> uptake at the surface. Outgassing of natural CO<sub>2</sub> occurs mostly in the tropics, especially in the equatorial upwelling region, and to a lesser extent in the North Pacific and polar Southern Ocean, mirroring a well-established understanding of regional patterns of air-sea CO<sub>2</sub> exchange (e.g., Takahashi et al., 2009, Gruber et al., 2009). These patterns are also noticeable in the Surface Ocean CO<sub>2</sub> Atlas (SOCAT) dataset, where an ocean fCO<sub>2</sub> value above the atmospheric level indicates outgassing (Figure B1). This map further illustrates the data-sparsity in the Indian Ocean and the southern hemisphere in general.

Interannual variability of the ocean carbon sink is driven by climate variability with a first-order effect from a stronger ocean sink during large El Niño events (e.g., 1997-1998) (Figure 10; Rödenbeck et al., 2014, Hauck et al., 2020; McKinley et al., 2017). The GOBMs show the same patterns of decadal variability as the mean of the fCO<sub>2</sub>-products, with a stagnation of the ocean sink in the 1990s and a strengthening since the early 2000s (Figure 10; Le Quéré et al., 2007; Landschützer et al., 2015, 2016; DeVries et al., 2017; Hauck et al., 2020; McKinley et al., 2020; Gruber et al., 2023). Different explanations have been proposed for this decadal variability, ranging from the ocean's response to changes in atmospheric wind and pressure systems (e.g., Le Quéré et al., 2007, Keppler and Landschützer, 2019), including variations in upper ocean overturning circulation (DeVries et al., 2017) to the eruption of Mount Pinatubo and its effects on sea surface temperature and slowed atmospheric CO<sub>2</sub> growth rate in the 1990s (McKinley et al., 2020). The main origin of the decadal variability is a matter of debate with a number of studies initially pointing to the Southern Ocean (see review in Canadell et al., 2021), but also contributions from the North Atlantic and North Pacific (Landschützer et al., 2016, DeVries et al., 2019), or a global signal (McKinley et al., 2020) were proposed.

Although all individual GOBMs and fCO<sub>2</sub>-products fall within the observational constraint, the ensemble means of GOBMs, and fCO<sub>2</sub>-products adjusted for the riverine flux diverge over time with a mean offset increasing from  $0.30$  GtC yr<sup>-1</sup> in the 1990s to  $0.57$  GtC yr<sup>-1</sup> in the decade 2013-2022 and reaching  $0.61$  GtC yr<sup>-1</sup> in 2022. The SO<sub>CEAN</sub> positive trend over time diverges by a factor two since 2002 (GOBMs:  $0.24 \pm 0.07$  GtC yr<sup>-1</sup> per decade, fCO<sub>2</sub>-products:  $0.48 \pm 0.11$  GtC yr<sup>-1</sup> per decade, SO<sub>CEAN</sub>:  $0.36$  GtC yr<sup>-1</sup> per decade) and by a factor of 2.5 since 2010 (GOBMs:  $0.16 \pm 0.15$  GtC yr<sup>-1</sup> per decade, fCO<sub>2</sub>-products:  $0.42 \pm 0.18$  GtC yr<sup>-1</sup> per decade; SO<sub>CEAN</sub>:

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0.29 GtC yr<sup>-1</sup> per decade). The  $f_{CO_2}$ -product estimate is slightly different compared to Friedlingstein et al. (2022b) as a result of an updated submission of the NIES-ML3 product (previously NIES-NN), however the difference in the integrated mean flux is small.

The discrepancy between the two types of estimates stems from a larger  $SO_{CEAN}$  trend in the northern and southern extra-tropics since around 2002 (Figure 13). Note that the discrepancy in the mean flux, which was located in the Southern Ocean in previous versions of the GCB, has been reduced due to the choice of the regional river flux adjustment (Lacroix et al., 2020, instead of Aumont et al., 2001). This comes at the expense of a new discrepancy in the mean  $SO_{CEAN}$  of about 0.2 GtC yr<sup>-1</sup> in the tropics. Likely explanations for the discrepancy in the trends in the high-latitudes are data sparsity and uneven data distribution (Bushinsky et al., 2019, Gloege et al., 2021, Hauck et al., 2023). In particular, two  $f_{CO_2}$ -products that are part of the GCB ensemble were shown to overestimate the Southern Ocean  $CO_2$  flux trend by 50 and 130% based on current sampling in a model subsampling experiment (Hauck et al., 2023). Another likely contributor to the discrepancy between GOBMs and  $f_{CO_2}$ -products are model biases (as indicated by the large model spread in the South, Figure 13, and the larger model-data  $f_{CO_2}$  mismatch, Figure B2).

In previous GCB releases, the ocean sink 1959-1989 was only estimated by GOBMs due to the absence of  $f_{CO_2}$  observations. Now, the first data-based estimates extending back to 1957/58 are becoming available (Jena-MLS, Rödenbeck et al., 2022, LDEO-HPD, Bennington et al., 2022; Gloege et al., 2022). These are based on a multilinear regression of  $pCO_2$  with environmental predictors (Rödenbeck et al., 2022) or on model-data  $pCO_2$  misfits and their relation to environmental predictors (Bennington et al., 2022). The Jena-MLS and LDEO-HPD estimates fall well within the range of GOBM estimates and have a correlation of 0.99 and 0.98 respectively with  $SO_{CEAN}$  for the period 1959-2022 (and 0.98 and 0.97 for the 1959-1989 period). They agree well on the mean  $SO_{CEAN}$  estimate since 1977 with a slightly higher amplitude of variability (Figure 10). Until 1976, Jena-MLS and LDEO-HPD are respectively about 0.25 GtCyr<sup>-1</sup> and about 0.1 GtCyr<sup>-1</sup> below the central  $SO_{CEAN}$  estimate. The agreement especially on phasing of variability is impressive in both products, and the discrepancies in the mean flux 1959-1976 could be explained by an overestimated trend of Jena-MLS (Rödenbeck et al., 2022). Bennington et al. (2022) report a larger flux into the pre-1990 ocean than in Jena-MLS, although lower than  $SO_{CEAN}$ .

The reported  $SO_{CEAN}$  estimate from GOBMs and  $f_{CO_2}$ -products is  $2.2 \pm 0.4$  GtC yr<sup>-1</sup> over the period 1994 to 2007, which is in excellent agreement with the ocean interior estimate of  $2.2 \pm 0.4$  GtC yr<sup>-1</sup>, which accounts for the climate effect on the natural  $CO_2$  flux of  $-0.4 \pm 0.24$  GtC yr<sup>-1</sup> (Gruber et al., 2019) to match the definition of  $SO_{CEAN}$  used here (Hauck et al., 2020). This comparison depends critically on the estimate of the climate effect on the natural  $CO_2$  flux, which is smaller from the GOBMs ( $-0.1$  GtC yr<sup>-1</sup>) than in Gruber et al. (2019). Uncertainties of these two estimates would also overlap when using the GOBM estimate of the climate effect on the natural  $CO_2$  flux.

During 2010-2016, the ocean  $CO_2$  sink appears to have intensified in line with the expected increase from atmospheric  $CO_2$  (McKinley et al., 2020). This effect is slightly stronger in the  $f_{CO_2}$ -products (Figure 10, ocean sink 2016 minus 2010, GOBMs:  $+0.42 \pm 0.10$  GtC yr<sup>-1</sup>,  $f_{CO_2}$ -products:  $+0.48 \pm 0.10$  GtC yr<sup>-1</sup>). The reduction of  $-0.14$  GtC yr<sup>-1</sup> (range:  $-0.39$  to  $+0.01$  GtC yr<sup>-1</sup>) in the ocean  $CO_2$  sink in 2017 is consistent with the return to

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normal conditions after the El Niño in 2015/16, which caused an enhanced sink in previous years. After an increasing  $S_{OCEAN}$  in 2018 and 2019, 2017, the GOBM and  $fCO_2$ -product ensemble means suggest a decrease of  $S_{OCEAN}$ , related to the triple La Niña event 2020-2023.

### 3.6.3 Final year 2022

The estimated ocean  $CO_2$  sink is  $2.8 \pm 0.4$  GtC for 2022. This is a small decrease of 0.05 GtC compared to 2021, in line with the expected sink weakening from persistent La Niña conditions. GOBM and  $fCO_2$ -product estimates consistently result in a near-stagnation of  $S_{OCEAN}$  (GOBMs:  $-0.01 \pm 0.05$  GtC,  $fCO_2$ -products:  $-0.09 \pm 0.10$  GtC). Four models and six  $fCO_2$ -products show a decrease in  $S_{OCEAN}$  (GOBMs down to  $-0.09$  GtC,  $fCO_2$ -products down to  $-0.25$  GtC), while one model shows no change and five models and two  $fCO_2$ -products show an increase in  $S_{OCEAN}$  (GOBMs up to 0.07 GtC,  $fCO_2$ -products up to 0.15 GtC; Figure 10). The  $fCO_2$ -products have a larger uncertainty at the end of the reconstructed time series (tail effect, e.g., Watson et al., 2020). Specifically, the  $fCO_2$ -products' estimate of the last year is regularly adjusted in the following release owing to the tail effect and an incrementally increasing data availability. While the monthly grid cells covered may have a lag of only about a year (Figure 10 inset), the values within grid cells may change with 1-5 years lag (see absolute number of observations plotted in previous GCB releases).

### 3.6.4 Year 2023 Projection

Using a feed-forward neural network method (see Section 2.5.2) we project an ocean sink of 2.9 GtC for 2023. This is slightly higher than for the year 2022 and could mark a reversal of the decreasing  $S_{OCEAN}$  sink trend of the past three years, due to the transition from persisting La Niña conditions to emerging El Niño conditions in 2023. The new set of ESMs predictions support this estimate with a 2023 ocean sink of around 3.1 [2.9, 3.2] GtC.

### 3.6.5 Ocean Models Evaluation

The process-based model evaluation draws a generally positive picture with GOBMs scattered around the observational values for Southern Ocean sea-surface salinity, Southern Ocean stratification index and surface ocean Revelle factor (Section C3.3 and Table A10). However, the Atlantic Meridional Overturning Circulation at 26°N is underestimated by 8 out of 10 GOBMs. It is planned to derive skill scores for the GOBMs in future releases based on these metrics.

The model simulations allow to separate the anthropogenic carbon component (steady state and non-steady state,  $\text{sim D} - \text{sim A}$ ) and to compare the model flux and DIC inventory change directly to the interior ocean estimate of Gruber et al. (2019) without further assumptions (Table A10). The GOBMs ensemble average of anthropogenic carbon inventory changes 1994-2007 amounts to  $2.4$  GtC  $\text{yr}^{-1}$  and is thus lower than the  $2.6 \pm 0.3$  GtC  $\text{yr}^{-1}$  estimated by Gruber et al. (2019) although within the uncertainty. Only four models with the highest sink estimate fall within the range reported by Gruber et al. (2019). This suggests that the majority of the GOBMs underestimate anthropogenic carbon uptake by 10-20%. Analysis of Earth System Models indicate that an underestimation by about 10% may be due to biases in ocean carbon transport and mixing from the surface mixed layer to the ocean interior (Goris et al., 2018, Terhaar et al., 2021, Bourgeois et al., 2022, Terhaar et al.,

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2022), biases in the chemical buffer capacity (Revelle factor) of the ocean (Vaittinada Ayar et al., 2022; Terhaar et al., 2022) and partly due to a late starting date of the simulations (mirrored in atmospheric CO<sub>2</sub> chosen for the preindustrial control simulation, Table A2, Bronselaer et al., 2017, Terhaar et al., 2022). Interestingly, and in contrast to the uncertainties in the surface CO<sub>2</sub> flux, we find the largest mismatch in interior ocean carbon accumulation in the tropics (96% of the mismatch), with minor contributions from the north (3%) and the south (<1%). These numbers deviate slightly from GCB2021 because of submission of the ACCESS model with a high anthropogenic carbon accumulation, particularly in the Southern Ocean. The large discrepancy in accumulation in the tropics highlights the role of interior ocean carbon redistribution for those inventories (Khatiwala et al., 2009, DeVries et al., 2023).

The evaluation of the ocean estimates with the fCO<sub>2</sub> observations from the SOCAT v2023 dataset for the period 1990-2022 shows an RMSE from annually detrended data of 0.4 to 2.4 μatm for the seven fCO<sub>2</sub>-products over the globe (Figure B2). The GOBMs RMSEs are larger and range from 2.9 to 5.4 μatm. The RMSEs are generally larger at high latitudes compared to the tropics, for both the fCO<sub>2</sub>-products and the GOBMs. The fCO<sub>2</sub>-products have RMSEs of 0.3 to 2.8 μatm in the tropics, 0.7 to 2.3 μatm in the north, and 0.7 to 2.8 μatm in the south. Note that the fCO<sub>2</sub>-products are based on the SOCAT v2023 database, hence the SOCAT is not an independent dataset for the evaluation of the fCO<sub>2</sub>-products. The GOBMs RMSEs are more spread across regions, ranging from 2.5 to 5.0 μatm in the tropics, 3.0 to 7.2 μatm in the North, and 3.7 to 8.5 μatm in the South. The higher RMSEs occur in regions with stronger climate variability, such as the northern and southern high latitudes (poleward of the subtropical gyres). The upper range of the model RMSEs have increased somewhat relative to Friedlingstein et al. (2022b).

## 3.7 Land Sink

### 3.7.1 Historical period 1850-2022

Cumulated since 1850, the terrestrial CO<sub>2</sub> sink amounts to  $225 \pm 55$  GtC, 32% of total anthropogenic emissions. Over the historical period, the sink increased in pace with the anthropogenic emissions exponential increase (Figure 3).

### 3.7.2 Recent period 1960-2022

The terrestrial CO<sub>2</sub> sink  $S_{\text{LAND}}$  increased from  $1.3 \pm 0.5$  GtC yr<sup>-1</sup> in the 1960s to  $3.3 \pm 0.8$  GtC yr<sup>-1</sup> during 2013-2022, with important interannual variations of up to 2 GtC yr<sup>-1</sup> generally showing a decreased land sink during El Niño events (Figure 8), responsible for the corresponding enhanced growth rate in atmospheric CO<sub>2</sub> concentration. The larger land CO<sub>2</sub> sink during 2013-2022 compared to the 1960s is reproduced by all the DGVMs in response to the increase in both atmospheric CO<sub>2</sub>, nitrogen deposition, and the changes in climate, and is consistent with constraints from the other budget terms (Table 5).

Over the period 1960 to present the increase in the global terrestrial CO<sub>2</sub> sink is largely attributed to the CO<sub>2</sub> fertilisation effect (Prentice et al., 2001, Piao et al., 2009, Schimel et al., 2015) and increased nitrogen deposition (Huntzinger et al., 2017, O'Sullivan et al., 2019), directly stimulating plant photosynthesis and increased plant water use in water limited systems, with a small negative contribution of climate change (Figure

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11). There is a range of evidence to support a positive terrestrial carbon sink in response to increasing atmospheric CO<sub>2</sub>, albeit with uncertain magnitude (Walker et al., 2021). As expected from theory, the greatest CO<sub>2</sub> effect is simulated in the tropical forest regions, associated with warm temperatures and long growing seasons (Hickler et al., 2008) (Figure 11a). However, evidence from tropical intact forest plots indicate an overall decline in the land sink across Amazonia (1985-2011), attributed to enhanced mortality offsetting productivity gains (Brienen et al., 2015, Hubau et al., 2020). During 2013-2022 the land sink is positive in all regions (Figure 6) with the exception of eastern Brazil, Bolivia, Paraguay, northern Venezuela, Southwest USA, central Europe and Central Asia, North and South Africa, and eastern Australia, where the negative effects of climate variability and change (i.e. reduced rainfall and/or increased temperature) counterbalance CO<sub>2</sub> effects. This is clearly visible on Figure 11 where the effects of CO<sub>2</sub> (Figure 11a) and climate (Figure 11b) as simulated by the DGVMs are isolated. The negative effect of climate is the strongest in most of South America, Central America, Southwest US, Central Europe, western Sahel, southern Africa, Southeast Asia and southern China, and eastern Australia (Figure 11b). Globally, over the 2013-2022 period, climate change reduces the land sink by  $0.68 \pm 0.62$  GtC yr<sup>-1</sup> (20% of S<sub>LAND</sub>). Most DGVMs have similar S<sub>LAND</sub> averaged over 2013-2022, and 14/20 models fall within the 1σ range of the residual land sink [2.0-3.8 GtC yr<sup>-1</sup>] (see Table 5), and all but one model are within the 2σ range [1.1-4.7 GtC yr<sup>-1</sup>]. The ED model is an outlier, with a land sink estimate of 5.7 GtC yr<sup>-1</sup>, driven by a strong CO<sub>2</sub> fertilisation effect (6.6 GtC yr<sup>-1</sup> in the CO<sub>2</sub> only (S1) simulation), that is offset by correspondingly high land-use emissions. There are no direct global observations of the land sink, or the CO<sub>2</sub> fertilisation effect, and so we are not yet in a position to rule out models based on component fluxes if the net land sink (S<sub>LAND</sub>-E<sub>LUC</sub>) is within the observational uncertainty provided by atmospheric O<sub>2</sub> measurements (Table 5). Overall, therefore the spread among models for the estimate of S<sub>LAND</sub> over the last decade has increased this year (0.8 GtC yr<sup>-1</sup>) compared to GCB2022 (0.6 GtC yr<sup>-1</sup>). Furthermore, DGVMs were compared against a data-constrained intermediate complexity model of the land carbon cycle (CARDAMOM) (Bloom and Williams, 2015; Bloom et al., 2016). Results suggest good correspondence between approaches at the interannual timescales, but divergence in the recent trend with CARDAMOM simulating a stronger trend than the DGVMs (Figure B8).

Since 2020 the globe has experienced La Niña conditions which would be expected to lead to an increased land carbon sink. A clear peak in the global land sink is not evident in S<sub>LAND</sub>, and we find that a La Niña- driven increase in tropical land sink is offset by a reduced high latitude extra-tropical land sink, which may be linked to the land response to recent climate extremes. A notable difference from GCB2022 (2012-2021 S<sub>LAND</sub> mean) is the reduced carbon losses across tropical drylands. Further, central Europe has switched from a sink of carbon to a source, with the summer heatwave of 2022 (and associated drought and wildfire) causing widespread losses (Peters et al., 2023). In the past years several regions experienced record-setting fire events. While global burned area has declined over the past decades mostly due to declining fire activity in savannas (Andela et al., 2017), forest fire emissions are rising and have the potential to counter the negative fire trend in savannas (Zheng et al., 2021). Noteworthy events include the 2019-2020 Black Summer event in Australia (emissions of roughly 0.2 GtC; van der Velde et al., 2021) and Siberia in 2021 where emissions approached 0.4 GtC or three

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3300 times the 1997-2020 average according to GFED4s. While other regions, including Western US and  
 3301 Mediterranean Europe, also experienced intense fire seasons in 2021 their emissions are substantially lower.

3302 Despite these regional negative effects of climate change on  $S_{\text{LAND}}$ , the efficiency of land to remove  
 3303 anthropogenic  $\text{CO}_2$  emissions has remained broadly constant over the last six decades, with a land-borne  
 3304 fraction ( $S_{\text{LAND}}/(E_{\text{FOS}}+E_{\text{LUC}})$ ) of around 30% (Figure 9b).

### 3305 3.7.3 Final year 2022

3306 The terrestrial  $\text{CO}_2$  sink from the DGVMs ensemble was  $3.8 \pm 0.8$  GtC in 2022, above the decadal average of  
 3307  $3.3 \pm 0.8$  GtC  $\text{yr}^{-1}$  (Figure 4, Table 7), and slightly above the 2021 sink of  $3.5 \pm 1.0$  GtC, likely driven by the  
 3308 persistent La Niña conditions. We note that the DGVMs estimate for 2022 is similar to the  $3.7 \pm 1.0$  GtC  $\text{yr}^{-1}$   
 3309 estimate from the residual sink from the global budget ( $E_{\text{FOS}}+E_{\text{LUC}}-G_{\text{ATM}}-S_{\text{OCEAN}}$ ) (Table 5).

### 3310 3.7.4 Year 2023 Projection

3311 Using a feed-forward neural network method we project a land sink of  $3.0$  GtC for 2023, 0.8 GtC smaller than  
 3312 the 2022 estimate. As for the ocean sink, we attribute this to the emerging El Niño conditions in 2023, leading to  
 3313 a reduced land sink. The ESMs do not provide an additional estimate of  $S_{\text{LAND}}$  as they only simulate the net  
 3314 atmosphere-land carbon flux ( $S_{\text{LAND}}-E_{\text{LUC}}$ ).

### 3315 3.7.5 Land Models Evaluation

3316 The evaluation of the DGVMs shows generally high skill scores across models for runoff, and to a lesser extent  
 3317 for vegetation biomass, GPP, and ecosystem respiration. These conclusions are supported by a more  
 3318 comprehensive analysis of DGVM performance in comparison with benchmark data (Seiler et al., 2022). A  
 3319 relative comparison of DGVM performance (Figure B3) suggests several DGVMs (CABLE-POP, CLASSIC,  
 3320 OCN, ORCHIDEE) may outperform others at multiple carbon and water cycle benchmarks. However, results  
 3321 from Seiler et al., 2022, also show how DGVM differences are often of similar magnitude compared with the  
 3322 range across observational datasets.

## 3323 3.8 Partitioning the carbon sinks

### 3324 3.8.1 Global sinks and spread of estimates

3325 In the period 2013-2022, the bottom-up view of global net ocean and land carbon sinks provided by the GCB,  
 3326  $S_{\text{OCEAN}}$  for the ocean and  $S_{\text{LAND}}-E_{\text{LUC}}$  for the land, agrees closely with the top-down global carbon sinks  
 3327 delivered by the atmospheric inversions. This is shown in Figure 12, which visualises the individual decadal  
 3328 mean atmosphere-land and atmosphere-ocean fluxes from each, along with the constraints on their sum offered  
 3329 by the global fossil  $\text{CO}_2$  emissions flux minus the atmospheric growth rate ( $E_{\text{FOS}}-G_{\text{ATM}}$ ,  $4.5 \pm 0.5$  GtC  $\text{yr}^{-1}$ ,  
 3330 Table 7, shown as diagonal line on Figure 12). The GCB estimate for net atmosphere-to-surface flux ( $S_{\text{OCEAN}} +$   
 3331  $S_{\text{LAND}} - E_{\text{LUC}}$ ) during 2013-2022 is  $4.9 \pm 1.2$  GtC  $\text{yr}^{-1}$  (Table 7), with the difference to the diagonal representing  
 3332 the budget imbalance ( $B_{\text{IM}}$ ) of  $0.4$  GtC  $\text{yr}^{-1}$  discussed in Section 3.9. By virtue of the inversion methodology, the

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imbalance of the top-down estimates is  $< 0.1 \text{ GtC yr}^{-1}$  and thus scatter across the diagonal, inverse models trading land for ocean fluxes in their solution. The independent constraint on the net atmosphere-to-surface flux based on atmospheric  $\text{O}_2$  is  $4.4 \pm 1.4 \text{ GtC yr}^{-1}$  over the 2013-2022 period (orange symbol on Figure 12), while the ESMs estimate for the net atmosphere-to-surface flux over that period is  $5.0 [4.2, 5.5] \text{ GtC yr}^{-1}$ , consistent with the GCB estimate (Tables 5 and 6).

The distributions based on the individual models and data products reveal substantial spread but converge near the decadal means quoted in Tables 5 to 7. Sink estimates for SOCEAN and from inverse systems are mostly non-Gaussian, while the ensemble of DGVMs appears more normally distributed justifying the use of a multi-model mean and standard deviation for their errors in the budget. Noteworthy is that the tails of the distributions provided by the land and ocean bottom-up estimates would not agree with the global constraint provided by the fossil fuel emissions and the observed atmospheric  $\text{CO}_2$  growth rate. This illustrates the power of the atmospheric joint constraint from  $\text{G}_{\text{ATM}}$  and the global  $\text{CO}_2$  observation network it derives from.

### 3.8.1.1 Net atmosphere-to-land fluxes

The GCB net atmosphere-to-land fluxes ( $\text{S}_{\text{LAND}} - \text{ELUC}$ ), calculated as the difference between  $\text{S}_{\text{LAND}}$  from the DGVMs and  $\text{ELUC}$  from the bookkeeping models, amounts to a  $2.1 \pm 1.1 \text{ GtC yr}^{-1}$  sink during 2013-2022 (Table 5). Estimates of net atmosphere-to-land fluxes ( $\text{S}_{\text{LAND}} - \text{ELUC}$ ) from the DGVMs alone ( $1.7 \pm 0.6 \text{ GtC yr}^{-1}$ , Table 5, green symbol on Figure 12) are slightly lower, within the uncertainty of the GCB estimate and also with the global carbon budget constraint from the ocean sink ( $\text{E}_{\text{FOS}} - \text{G}_{\text{ATM}} - \text{SOCEAN}$ ,  $1.6 \pm 0.6 \text{ GtC yr}^{-1}$ , Table 7). For the last decade (2013-2022), the inversions estimate the net atmosphere-to-land uptake to be  $1.6 [0.5, 2.3] \text{ GtC yr}^{-1}$ , similar to the DGVMs estimates (purple symbol on Figure 12). The ESMs estimate for the net atmosphere-to-land uptake during 2013-2022 is  $2.4 [1.8, 3.3] \text{ GtC yr}^{-1}$ , consistent with the GCB and DGVMs estimates of  $\text{S}_{\text{LAND}} - \text{ELUC}$  (Figure 13 top row). The independent constraint based on atmospheric  $\text{O}_2$  is significantly lower,  $1.1 \pm 1.3 \text{ GtC yr}^{-1}$ , although its relatively high uncertainty range overlaps with the central estimates from other approaches.

### 3.8.1.2 Net atmosphere-to-ocean fluxes

For the 2013-2022 period, the GOBMs ( $2.6 \pm 0.4 \text{ GtC yr}^{-1}$ ) produce a lower estimate for the ocean sink than the  $\text{fCO}_2$ -products ( $3.1 [2.6, 3.3] \text{ GtC yr}^{-1}$ ), which shows up in Figure 12 as separate peaks in the distribution from the GOBMs (dark blue symbols) and from the  $\text{fCO}_2$ -products (light blue symbols). Atmospheric inversions ( $3.0 [2.4, 4.1] \text{ GtC yr}^{-1}$ ) suggest an ocean uptake more in line with the  $\text{fCO}_2$ -products for the recent decade (Table 7), although the inversions range includes both the GOBMs and  $\text{fCO}_2$ -products estimates (Figure 13 top row). The ESMs  $2.6 [2.2, 3.4] \text{ GtC yr}^{-1}$  suggest a moderate estimate for the ocean carbon sink, comparable to the GOBMs estimate with regard to mean and spread. Conversely, the independent constraint based on atmospheric  $\text{O}_2$  suggests a larger ocean sink ( $3.3 \pm 0.6 \text{ GtC yr}^{-1}$ ), more consistent with the  $\text{fCO}_2$ -products and atmospheric inversions. We caution that the riverine transport of carbon taken up on land and outgassing from the ocean is a substantial ( $0.65 \pm 0.3 \text{ GtC yr}^{-1}$ ) and uncertain term (Crisp et al., 2022; Gruber et al., 2023; DeVries et al., 2023) that separates the GOBMs, ESMs and oxygen-based estimates on the one hand from the  $\text{fCO}_2$ -products and atmospheric inversions on the other hand. However, the high ocean sink estimate based on atmospheric oxygen

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that is not subject to river flux adjustment, provides another line of evidence that most GOBMs and ESMs underestimate the ocean sink.

### 3.8.2 Regional partitioning

Figure 13 shows the latitudinal partitioning of the global atmosphere-to-ocean ( $S_{\text{OCEAN}}$ ), atmosphere-to-land ( $S_{\text{LAND}} - E_{\text{LUC}}$ ), and their sum ( $S_{\text{OCEAN}} + S_{\text{LAND}} - E_{\text{LUC}}$ ) according to the estimates from GOBMs and ocean  $f\text{CO}_2$  products ( $S_{\text{OCEAN}}$ ), DGVMs ( $S_{\text{LAND}} - E_{\text{LUC}}$ ), and from atmospheric inversions ( $S_{\text{OCEAN}}$  and  $S_{\text{LAND}} - E_{\text{LUC}}$ ).

#### 3.8.2.1 North

Despite being one of the most densely observed and studied regions of our globe, annual mean carbon sink estimates in the northern extra-tropics (north of  $30^\circ\text{N}$ ) continue to differ. The atmospheric inversions suggest an atmosphere-to-surface sink ( $S_{\text{OCEAN}} + S_{\text{LAND}} - E_{\text{LUC}}$ ) for 2013-2022 of  $2.8[1.7 \text{ to } 3.3] \text{ GtC yr}^{-1}$ , which is higher than the process models' estimate of  $2.2 \pm 0.4 \text{ GtC yr}^{-1}$  (Figure 13). The GOBMs ( $1.2 \pm 0.2 \text{ GtC yr}^{-1}$ ),  $f\text{CO}_2$ -products ( $1.3[1.2-1.4] \text{ GtC yr}^{-1}$ ), and inversion systems ( $1.2[0.7 \text{ to } 1.4] \text{ GtC yr}^{-1}$ ) produce consistent estimates of the ocean sink. Thus, the difference mainly arises from the net land flux ( $S_{\text{LAND}} - E_{\text{LUC}}$ ) estimate, which is  $1.0 \pm 0.4 \text{ GtC yr}^{-1}$  in the DGVMs compared to  $1.6[0.4 \text{ to } 2.6] \text{ GtC yr}^{-1}$  in the atmospheric inversions (Figure 13, second row). We note that the range among inversions driven by OCO-2 satellite data is smaller though ( $1.6 - 2.2 \text{ GtC yr}^{-1}$   $N=6$ ), supporting the notion that northern extra-tropics land uptake was larger than suggested by the DGVMs at least in the 2015-2022 period covered by this data product.

Discrepancies in the northern land fluxes conforms with persistent issues surrounding the quantification of the drivers of the global net land  $\text{CO}_2$  flux (Armeth et al., 2017; Huntzinger et al., 2017; O'Sullivan et al., 2022) and the distribution of atmosphere-to-land fluxes between the tropics and high northern latitudes (Baccini et al., 2017; Schimel et al., 2015; Stephens et al., 2007; Ciais et al., 2019; Gaubert et al., 2019).

In the northern extra-tropics, the process models, inversions, and  $f\text{CO}_2$ -products consistently suggest that most of the variability stems from the land (Figure 13). Inversions generally estimate similar interannual variations (IAV) over land to DGVMs ( $0.28-0.35$  vs  $0.8-0.64 \text{ GtC yr}^{-1}$ , averaged over 1990-2022), and they have higher IAV in ocean fluxes ( $0.05-0.10 \text{ GtC yr}^{-1}$ ) relative to GOBMs ( $0.02-0.06 \text{ GtC yr}^{-1}$ , Figure B2), and  $f\text{CO}_2$ -products ( $0.03-0.10 \text{ GtC yr}^{-1}$ ).

#### 3.8.2.2 Tropics

In the tropics ( $30^\circ\text{S}-30^\circ\text{N}$ ), both the atmospheric inversions and process models estimate a net carbon balance ( $S_{\text{OCEAN}} + S_{\text{LAND}} - E_{\text{LUC}}$ ) that is close to neutral over the past decade. The GOBMs ( $-0.03 \pm 0.24 \text{ GtC yr}^{-1}$ ),  $f\text{CO}_2$ -products ( $0.2[0.2, 0.3] \text{ GtC yr}^{-1}$ ), and inversion systems ( $-0.3[-0.1, 0.8] \text{ GtC yr}^{-1}$ ) all indicate an approximately neutral tropical ocean flux (see Figure B1 for spatial patterns). DGVMs indicate a net land sink ( $S_{\text{LAND}} - E_{\text{LUC}}$ ) of  $0.6 \pm 0.4 \text{ GtC yr}^{-1}$ , whereas the inversion systems indicate a net land flux of  $0.03[-0.8, 1.1] \text{ GtC yr}^{-1}$ , though with high uncertainty (Figure 13, third row).

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The tropical lands are the origin of most of the atmospheric CO<sub>2</sub> interannual variability (Ahlström et al., 2015), consistently among the process models and inversions (Figure 13). The interannual variability in the tropics is similar among the ocean  $\text{CO}_2$ -products ( $0.07\text{--}0.16\text{ GtC yr}^{-1}$ ) and the GOBMs ( $0.07\text{--}0.16\text{ GtC yr}^{-1}$ , Figure B2), which is the highest ocean sink variability of all regions. The DGVMs and inversions indicate that atmosphere-to-land CO<sub>2</sub> fluxes are more variable than atmosphere-to-ocean CO<sub>2</sub> fluxes in the tropics, with interannual variability of  $0.35$  to  $1.61$  and  $0.77\text{--}0.92\text{ GtC yr}^{-1}$  for DGVMs and inversions, respectively.

### 3.8.2.3 South

In the southern extra-tropics (south of 30°S), the atmospheric inversions suggest a  $\text{net}$  atmosphere-to-surface sink ( $\text{SOCEAN} + \text{SLAND} - \text{ELUC}$ ) for 2013–2022 of  $1.5 [1.2, 1.9]\text{ GtC yr}^{-1}$ , slightly higher than the process models' estimate of  $1.5 \pm 0.4\text{ GtC yr}^{-1}$  (Figure 13). An approximately neutral  $\text{net}$  land flux ( $\text{SLAND} - \text{ELUC}$ ) for the southern extra-tropics is estimated by both the DGVMs ( $0.05 \pm 0.07\text{ GtC yr}^{-1}$ ) and the inversion systems (sink of  $0.02 [-0.2, 0.2]\text{ GtC yr}^{-1}$ ). This means nearly all carbon uptake is due to oceanic sinks south of 30°S. The Southern Ocean flux in the  $\text{CO}_2$ -products ( $1.6 [1.3, 1.7]\text{ GtC yr}^{-1}$ ) and inversion estimates ( $1.5 [1.3, 1.9]\text{ GtC yr}^{-1}$ ) is slightly higher than in the GOBMs ( $1.4 \pm 0.3\text{ GtC yr}^{-1}$ ) (Figure 13, bottom row). This discrepancy in the mean flux is smaller this year than in previous releases due to the change in data set of the regional distribution of the river flux adjustment applied to  $\text{CO}_2$ -products and inverse systems to isolate the anthropogenic  $\text{SOCEAN}$  flux. The data set used (Lacroix et al., 2020) has less river-induced carbon outgassing in the Southern Ocean than the previously used data set (Aumont et al., 2001). Nevertheless, the time-series of atmospheric inversions and  $\text{CO}_2$ -products diverge from the GOBMs. A substantial overestimation of the trends in the  $\text{CO}_2$ -products could be explained by sparse and unevenly distributed observations, especially in wintertime (Figure B1; Hauck et al., 2023; Gloege et al., 2021). Model biases may contribute as well, with biases in mode water formation, stratification, and the chemical buffer capacity known to play a role in Earth System Models (Terhaar et al., 2021, Bourgeois et al., 2022, Terhaar et al., 2022).

The interannual variability in the southern extra-tropics is low because of the dominance of ocean areas with low variability compared to land areas. The split between land ( $\text{SLAND} - \text{ELUC}$ ) and ocean ( $\text{SOCEAN}$ ) shows a substantial contribution to variability in the south coming from the land, with no consistency between the DGVMs and the inversions or among inversions. This is expected due to the difficulty of separating exactly the land and oceanic fluxes when viewed from atmospheric observations alone. The  $\text{SOCEAN}$  interannual variability was found to be higher in the  $\text{CO}_2$ -products ( $0.04\text{--}0.18\text{ GtC yr}^{-1}$ ) compared to GOBMs ( $0.03$  to  $0.06\text{ GtC yr}^{-1}$ ) in 1990–2022 (Figure B2). Model subsampling experiments recently illustrated that  $\text{CO}_2$ -products may overestimate decadal variability in the Southern Ocean carbon sink by 30% and the trend since 2000 by 50–130% due to data sparsity, based on one and two  $\text{CO}_2$ -products with strong variability (Gloege et al., 2021, Hauck et al., 2023).

### 3.8.2.4 RECCAP2 regions

Aligning with the RECCAP-2 initiative (Ciais et al., 2022; Poulter et al., 2022; DeVries et al., 2023), we provide an overview of  $\text{ELUC}$ ,  $\text{SLAND}$ , Net land ( $\text{SLAND} - \text{ELUC}$ ), and  $\text{SOCEAN}$  fluxes for 10 land regions, and 5 ocean regions, averaged over the period 2013–2022. The DGVMs and inversions suggest a positive net land sink in all

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regions, except for South America and Africa, where the inversions indicate a small net source of respectively -  
 $0.1 [-0.5, 0.3] \text{ GtC yr}^{-1}$  and  $-0.3 [-0.6, -0.1] \text{ GtC yr}^{-1}$ , compared to a small sink of  $0.1 \pm 0.3 \text{ GtC yr}^{-1}$  and  
 $0.3 \pm 0.2 \text{ GtC yr}^{-1}$  for the DGVMs. However, for South America, there is substantial uncertainty in both products  
(ensembles span zero). For the DGVMs, this is driven by uncertainty in both  $S_{\text{LAND}}$  ( $0.6 \pm 0.5 \text{ GtC yr}^{-1}$ ) and  $E_{\text{LUC}}$   
( $0.4 \pm 0.2 \text{ GtC yr}^{-1}$ ). The bookkeeping models also suggest an  $E_{\text{LUC}}$  source of around  $0.4 \text{ GtC yr}^{-1}$  in South  
America and Africa, in line with the DGVMs estimates. Bookkeeping models and DGVMs similarly estimate a  
loss of  $0.4 \text{ GtC yr}^{-1}$  in Southeast Asia, with DGVMs suggesting a near neutral net land sink ( $0.03 \pm 0.12 \text{ GtC}$   
 $\text{yr}^{-1}$ ). This contrasts the inversion estimate of a  $0.2 [-0.3, 0.6] \text{ GtC yr}^{-1}$  sink, although the ensemble spread is  
substantial. The inversions suggest the largest net land sinks are located in North America ( $0.5 [-0.1, 0.8] \text{ GtC}$   
 $\text{yr}^{-1}$ ), Russia ( $0.7 [0.5, 1.1] \text{ GtC yr}^{-1}$ ), and East Asia ( $0.3 [0.0, 0.9] \text{ GtC yr}^{-1}$ ). This agrees well with the DGVMs  
in North America ( $0.4 \pm 0.2 \text{ GtC yr}^{-1}$ ), which indicate a large natural land sink ( $S_{\text{LAND}}$ ) of  $0.6 \pm 0.2 \text{ GtC yr}^{-1}$ ,  
being slightly reduced by land-use related carbon losses ( $0.2 \pm 0.1 \text{ GtC yr}^{-1}$ ). The DGVMs suggest a smaller net  
land sink in Russia compared to inversions ( $0.4 \pm 0.2 \text{ GtC yr}^{-1}$ ), and a similar net sink in East Asia ( $0.2 \pm 0.1 \text{ GtC}$   
 $\text{yr}^{-1}$ ).

There is generally a higher level of agreement in regional  $S_{\text{OCEAN}}$  estimates between the different data streams  
(GOBMs,  $f\text{CO}_2$ -products and atmospheric inversions) on decadal scale, compared to the land flux estimates. All  
data streams agree that the largest contribution to  $S_{\text{OCEAN}}$  stems from the Southern Ocean, with important  
contributions also from the vast ocean basins in the Atlantic and Pacific oceans. In the Southern Ocean, GOBMs  
suggest a sink of  $1.0 \pm 0.3 \text{ GtC yr}^{-1}$ , in line with the  $f\text{CO}_2$ -products ( $1.1 [0.9, 1.2] \text{ GtC yr}^{-1}$ ) and atmospheric  
inversions ( $1.0 [0.8, 1.4] \text{ GtC yr}^{-1}$ ). There is similar agreement in the Pacific ocean, with GOBMs,  $f\text{CO}_2$ -  
products, and atmospheric inversions indicating a sink of  $0.5 \pm 0.1 \text{ GtC yr}^{-1}$ ,  $0.7 [0.5, 0.9] \text{ GtC yr}^{-1}$ , and  $0.6$   
 $[0.2, 1.0] \text{ GtC yr}^{-1}$ , respectively. However, in the Atlantic ocean, GOBMs simulate a sink of  $0.5 \pm 0.1 \text{ GtC yr}^{-1}$ ,  
noticeably lower than both the  $f\text{CO}_2$ -products ( $0.8 [0.7, 0.9] \text{ GtC yr}^{-1}$ ) and atmospheric inversions ( $0.8 [0.5, 1.2]$   
 $\text{GtC yr}^{-1}$ ). It is important to note the  $f\text{CO}_2$ -products and atmospheric inversions have a substantial and uncertain  
river flux adjustment in the Atlantic ocean ( $0.3 \text{ GtC yr}^{-1}$ ) that also leads to a mean offset between GOBMs and  
 $f\text{CO}_2$ -products/inversions in the latitude band of the tropics (Figure 13). The Indian Ocean due its smaller size  
and the Arctic Ocean due to its size and sea-ice cover that prevents air-sea gas-exchange are responsible for  
smaller but non negligible  $S_{\text{OCEAN}}$  fluxes (Indian Ocean:  $0.3 [0.2, 0.4] \text{ GtC yr}^{-1}$ ,  $0.3 [0.3, 0.4] \text{ GtC yr}^{-1}$ , and  $0.4$   
 $[0.3, 0.6] \text{ GtC yr}^{-1}$  for GOBMs,  $f\text{CO}_2$ -products, and atmospheric inversions, respectively, and Arctic Ocean:  $0.1$   
 $[0.1, 0.1] \text{ GtC yr}^{-1}$ ,  $0.2 [0.2, 0.2] \text{ GtC yr}^{-1}$ , and  $0.1 [0.1, 0.1] \text{ GtC yr}^{-1}$  for GOBMs,  $f\text{CO}_2$ -products, and  
atmospheric inversions, respectively). Note that the  $S_{\text{OCEAN}}$  numbers presented here deviate from numbers  
reported in RECCAP-2 where the net air-sea  $\text{CO}_2$  flux is reported (i.e. without river flux adjustment for  $f\text{CO}_2$ -  
products and inversions, and with river flux adjustment subtracted from GOBMs in most chapters, or comparing  
unadjusted data sets with discussion of uncertain regional riverine fluxes as major uncertainty, e.g. Sarma et al.,  
2023, DeVries et al., 2023).

### 3.8.2.5 Tropical vs northern land uptake

A continuing conundrum is the partitioning of the global atmosphere-land flux between the northern hemisphere land and the tropical land (Stephens et al., 2017; Pan et al., 2011; Gaubert et al., 2019). It is of importance because each region has its own history of land-use change, climate drivers, and impact of increasing atmospheric CO<sub>2</sub> and nitrogen deposition. Quantifying the magnitude of each sink is a prerequisite to understanding how each individual driver impacts the tropical and mid/high-latitude carbon balance.

We define the North-South (N-S) difference as net atmosphere-land flux north of 30°N minus the net atmosphere-land flux south of 30°N. For the inversions, the N-S difference ranges from  $-0.5 \text{ GtC yr}^{-1}$  to  $+3.0 \text{ GtC yr}^{-1}$  across this year's inversion ensemble, but with a clear cluster of solutions driven by the OCO-2 satellite product with a NH land sink of  $1.6\text{--}2.2 \text{ GtC yr}^{-1}$ , along with a tropical land flux of  $-0.6$  to  $+0.2 \text{ GtC yr}^{-1}$ , and a dipole between  $+1.4$  and  $+2.8 \text{ GtC yr}^{-1}$  for the period 2015–2022. Whether this tighter clustering relative to the surface-observation based inversions is driven by (a) additional information on tropical fluxes delivered by tropical retrievals contained in OCO-2, (b) a tighter constraint on the NH land sink from that same product, or (c) a reduced sensitivity to vertical transport differences between models when using CO<sub>2</sub> column integrals, requires further investigation.

In the ensemble of DGVMs the N-S difference is  $0.5 \pm 0.6 \text{ GtC yr}^{-1}$ , a much narrower range than the one from atmospheric inversions. Five DGVMs have a N-S difference larger than  $1.0 \text{ GtC yr}^{-1}$ , compared to only two from last year's ensemble. This is still only 25% of DGVMs, compared to most inversion systems simulating a difference at least this large. The smaller spread across DGVMs than across inversions is to be expected as there is no correlation between Northern and Tropical land sinks in the DGVMs as opposed to the inversions where the sum of the two regions being well-constrained by atmospheric observations leads to an anti-correlation between these two regions. This atmospheric N-S gradient could be used as an additional way to evaluate tropical and NH uptake in DGVMs, if their fluxes were combined with multiple transport models. Vice versa, the much smaller spread in the N-S difference between the DGVMs could help to scrutinise the inverse systems further. For example, a large northern land sink and a tropical land source in an inversion would suggest a large sensitivity to CO<sub>2</sub> fertilisation (the dominant factor driving the land sinks) for Northern ecosystems, which would be not mirrored by tropical ecosystems. Such a combination could be hard to reconcile with the process understanding gained from the DGVM ensembles and independent measurements (e.g. Free Air CO<sub>2</sub> Enrichment experiments).

### 3.8.3 Forest Fires in 2023

Fire emissions so far in 2023 have been above the average of recent decades, due to an extreme wildfire season in North America. Figure B9 shows global and regional emissions estimates for the period 1st Jan–30th September in each year 2003–2023. Estimates derive from two global fire emissions products: the global fire emissions database (GFED, version 4.1s; van der Werf et al., 2017), and; the global fire assimilation system (GFAS, operated by the Copernicus Atmosphere Service; Di Giuseppe et al., 2018). The two products estimate that global emissions from fires were  $1.5\text{--}1.8 \text{ GtC yr}^{-1}$  during January–September 2023. These estimates are 13–

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15% above the 2013-2022 average for the same months (1.3-1.6 GtC yr<sup>-1</sup>) and 7-9% above the 2003-2022 average (1.4-1.6 GtC yr<sup>-1</sup>).

The above-average global fire emissions during January-September 2023 have occurred despite below-average fire emissions from major source regions. On average during 2013-2022, 72-79% of global fire emissions through September occur in the tropics (0.9-1.3 GtC yr<sup>-1</sup>) and around half of global fire emissions through September occur in Africa (0.6-0.8 GtC yr<sup>-1</sup>). This year, through September, fire emissions in the tropics (0.7-0.9 GtC yr<sup>-1</sup>) were 7-23% below the 2013-2022 average and fire emissions in Africa (0.5-0.7 GtC yr<sup>-1</sup>) were 7-17% below the 2013-2022 average.

In contrast, fire emissions from the Northern extra-tropics so far in 2023 have exceeded the values of all previous years 2003-2022. Northern extra-tropical emissions during January-September 2023 (0.6-0.8 GtC yr<sup>-1</sup>) were 80-160% above the average for the same months in the past decade (0.3 GtC yr<sup>-1</sup> for both global fire emissions products). Fire emissions in North America alone (0.5-0.7 GtC yr<sup>-1</sup>) were 220-380% above the average of the past decade (0.1 GtC yr<sup>-1</sup> for both products). In both products, North America was the only RECCAP2 region with above-average fire C emissions for January-September in 2023.

While the fire emission fluxes presented above point towards a highly unusual Northern Hemisphere fire season so far in 2023, we caution that the fluxes presented should not be compared directly with other fluxes of the budget (e.g. S<sub>LAND</sub> or E<sub>LUC</sub>) due to incompatibilities between the observable fire emission fluxes and what is quantified in the S<sub>LAND</sub> and E<sub>LUC</sub> components of the budget. The fire emission estimates from global fire products relate to all fire types that can be observed in Earth Observations (Giglio et al., 2018; Randerson et al., 2012; Kaiser et al., 2012), including (i) fires occurring as part of natural disturbance-recovery cycles that would also have occurred in the pre-industrial period (Yue et al., 2016; Keeley and Pausas, 2019; Zou et al., 2019), (ii) fires occurring above and beyond natural disturbance-recovery cycle due to changes in climate, CO<sub>2</sub> and N fertilisation and to an increased frequency of extreme drought and heatwave events (Abatzoglou et al., 2019; Jones et al., 2022; Zheng et al., 2021; Burton et al., 2023), and (iii) fires occurring in relation to land use and land use change, such as deforestation fires and agricultural fires (van der Werf et al., 2010; Magi et al., 2012).

In the context of the global carbon budget, only the portion of fire emissions associated with (ii) should be included in the S<sub>LAND</sub> component, and fire emissions associated with (iii) should already be accounted for in the E<sub>LUC</sub> component. Emissions associated with (i) should not be included in the global carbon budget. It is not currently possible to derive specific estimates for fluxes (i), (ii), and (iii) using global fire emission products such as GFED or GFAS. In addition, the fire emissions estimates from global fire emissions products represent a gross flux of carbon to the atmosphere, whereas the S<sub>LAND</sub> component of the budget is a net flux that should also include post-fire recovery fluxes. Even if emissions from fires of type (ii) could be separated from those of type (i), these fluxes may be partially or wholly offset in subsequent years by post-fire fluxes as vegetation recovers, sequestering carbon from the atmosphere to the terrestrial biosphere (Yue et al., 2016).

### 3.9 Closing the Global Carbon Cycle

#### 3.9.1 Partitioning of Cumulative Emissions and Sink Fluxes

The global carbon budget over the historical period (1850–2021) is shown in Figure 3.

Emissions during the period 1850–2022 amounted to  $695 \pm 70$  GtC and were partitioned among the atmosphere ( $280 \pm 5$  GtC; 40%), ocean ( $180 \pm 35$  GtC; 26%), and land ( $225 \pm 55$  GtC; 32%). The cumulative land sink is almost equal to the cumulative land-use emissions ( $220 \pm 70$  GtC), making the global land nearly neutral over the whole 1850–2022 period.

The use of nearly independent estimates for the individual terms of the global carbon budget shows a cumulative budget imbalance of 15 GtC (2% of total emissions) during 1850–2022 (Figure 3, Table 8), which, if correct, suggests that emissions could be slightly too high by the same proportion (2%) or that the combined land and ocean sinks are slightly underestimated (by about 3%), although these are well within the uncertainty range of each component of the budget. Nevertheless, part of the imbalance could originate from the estimation of significant increase in  $E_{\text{FOS}}$  and  $E_{\text{LUC}}$  between the mid 1920s and the mid 1960s which is unmatched by a similar growth in atmospheric  $\text{CO}_2$  concentration as recorded in ice cores (Figure 3). However, the known loss of additional sink capacity of 30–40 GtC (over the 1850–2020 period) due to reduced forest cover has not been accounted for in our method and would exacerbate the budget imbalance (see Section 2.10 and Appendix D.4).

For the more recent 1960–2022 period where direct atmospheric  $\text{CO}_2$  measurements are available, total emissions ( $E_{\text{FOS}} + E_{\text{LUC}}$ ) amounted to  $485 \pm 50$  GtC, of which  $395 \pm 20$  GtC (82%) were caused by fossil  $\text{CO}_2$  emissions, and  $90 \pm 45$  GtC (18%) by land-use change (Table 8). The total emissions were partitioned among the atmosphere ( $215 \pm 5$  GtC; 44%), ocean ( $125 \pm 25$  GtC; 25%), and the land ( $150 \pm 35$  GtC; 31%), with a near zero ( $-5$  GtC) unattributed budget imbalance. All components except land-use change emissions have significantly grown since 1960, with important interannual variability in the growth rate in atmospheric  $\text{CO}_2$  concentration and in the land  $\text{CO}_2$  sink (Figure 4), and some decadal variability in all terms (Table 7).

Differences with previous budget releases are documented in Figure B5.

The global carbon budget averaged over the last decade (2013–2022) is shown in Figure 2, Figure 14 (right panel) and Table 7. For this period, 88% of the total emissions ( $E_{\text{FOS}} + E_{\text{LUC}}$ ) were from fossil  $\text{CO}_2$  emissions ( $E_{\text{FOS}}$ ), and 12% from land-use change ( $E_{\text{LUC}}$ ). The total emissions were partitioned among the atmosphere (47%), ocean (26%) and land (21%), with a small unattributed budget imbalance ( $-4\%$ ). For single years, the budget imbalance can be larger (Figure 4). For 2022, the combination of our estimated sources ( $11.1 \pm 0.9$  GtC  $\text{yr}^{-1}$ ) and sinks ( $11.2 \pm 0.9$  GtC  $\text{yr}^{-1}$ ) leads to a  $\text{BIM}$  of  $-0.09$  GtC, suggesting a near closure of the global carbon budget, although there is relatively high uncertainty on  $\text{BIM}$  ( $\pm 1.3$  GtC for 2022) as this is calculated as the residual of the five budget terms.

#### 3.9.2 Trend and Variability in the Carbon Budget Imbalance

The carbon budget imbalance ( $\text{BIM}$ ; Eq. 1, Figure 4) quantifies the mismatch between the estimated total emissions and the estimated changes in the atmosphere, land, and ocean reservoirs. The budget imbalance from

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Deleted: 2021...022 (Figure 3, Table 8), which, if correct, suggests that emissions could be slightly too high by the same proportion (2%) or that the combined land and ocean sinks are slightly underestimated (by about 3%), although these are well within the uncertainty range of each component of the budget. Nevertheless, part of the imbalance could originate from the estimation of significant increase in  $E_{\text{FOS}}$  and  $E_{\text{LUC}}$  between the mid 1920s and the mid 1960s which is unmatched by a similar growth in atmospheric  $\text{CO}_2$  concentration as recorded in ice cores (Figure 3). However, the known loss of additional sink capacity of 30–40 GtC (over the 1850–2020 period) due to reduced forest cover has not been accounted for in our method and would exacerbate the budget imbalance (see Section 2.10 and Appendix D.4 (... [93])

Deleted: 2021...022 period where direct atmospheric  $\text{CO}_2$  measurements are available, total emissions ( $E_{\text{FOS}} + E_{\text{LUC}}$ ) amounted to  $470 \dots 85 \pm 50$  GtC, of which  $385 \dots 95 \pm 20$  GtC (82%) were caused by fossil  $\text{CO}_2$  emissions, and  $85 \dots 0 \pm 45$  GtC (18%) by land-use change (Table 8). The total emissions were partitioned among the atmosphere ( $210 \dots 15 \pm 5$  GtC; 45...4%), ocean ( $120 \dots 25 \pm 25$  GtC; 26...5%), and the land ( $145 \pm 30 \dots 50 \pm 35$  GtC; 30...1%), with a near zero ( $-5$  GtC) unattributed budget imbalance. All components except land-use change emissions have significantly grown since 1960, with important interannual variability in the growth rate in atmospheric  $\text{CO}_2$  concentration and in the land  $\text{CO}_2$  sink (Figure 4), and some decadal variability in all terms (... [94])

Deleted: 2012–2021...013–2022) is shown in Figure 2, Figure 14 (right panel) and Table 6.... For this period, 89...8% of the total emissions ( $E_{\text{FOS}} + E_{\text{LUC}}$ ) were from fossil  $\text{CO}_2$  emissions ( $E_{\text{FOS}}$ ), and 11...2% from land-use change ( $E_{\text{LUC}}$ ). The total emissions were partitioned among the atmosphere (48...7%), ocean (26%) and land (29...1%), with a near-zero...small unattributed budget imbalance ( $-3\%$ ). For single years, the budget imbalance can be larger (Figure 4). For 2021...022, the combination of our estimated sources (10.9... (... [95])

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1960 to 2022 is very small ( $-3.0$  GtC over the period, i.e. average of  $0.05$  GtC yr<sup>-1</sup>) and shows no trend over the full time series (Figure 4e). The process models (GOBMs and DGVMs) and data-products have been selected to match observational constraints in the 1990s, but no further constraints have been applied to their representation of trend and variability. Therefore, the near-zero mean and trend in the budget imbalance is seen as evidence of a coherent community understanding of the emissions and their partitioning on those time scales (Figure 4). However, the budget imbalance shows substantial variability of the order of  $\pm 1$  GtC yr<sup>-1</sup>, particularly over semi-decadal time scales, although most of the variability is within the uncertainty of the estimates. The positive carbon imbalance during the 1960s, and early 1990s, indicates that either the emissions were overestimated, or the sinks were underestimated during these periods. The reverse is true for the 1970s, and to a lesser extent for the 1980s and 2013-2022 period (Figure 4, Table 7).

We cannot attribute the cause of the variability in the budget imbalance with our analysis, we only note that the budget imbalance is unlikely to be explained by errors or biases in the emissions alone because of its large semi-decadal variability component, a variability that is atypical of emissions and has not changed in the past 60 years despite a near tripling in emissions (Figure 4). Errors in S<sub>LAND</sub> and S<sub>OCEAN</sub> are more likely to be the main cause for the budget imbalance, especially on interannual to semi-decadal timescales. For example, underestimation of the S<sub>LAND</sub> by DGVMs has been reported following the eruption of Mount Pinatubo in 1991 possibly due to missing responses to changes in diffuse radiation (Mercado et al., 2009). Although since GCB2021 we accounted for aerosol effects on solar radiation quantity and quality (diffuse vs direct), most DGVMs only used the former as input (i.e., total solar radiation) (Table A1). Thus, the ensemble mean may not capture the full effects of volcanic eruptions, i.e. associated with high light scattering sulphate aerosols, on the land carbon sink (O'Sullivan et al., 2021). DGVMs are suspected to overestimate the land sink in response to the wet decade of the 1970s (Sitch et al., 2008). Quasi-decadal variability in the ocean sink has also been reported, with all methods agreeing on a smaller than expected ocean CO<sub>2</sub> sink in the 1990s and a larger than expected sink in the 2000s (Figure 10; Landschützer et al., 2016, DeVries et al., 2019, Hauck et al., 2020, McKinley et al., 2020, Gruber et al., 2023) and the climate-driven variability could be substantial but is not well constrained (DeVries et al., 2023, Müller et al., 2023). Errors in sink estimates could also be driven by errors in the climatic forcing data, particularly precipitation for S<sub>LAND</sub> and wind for S<sub>OCEAN</sub>. Also, the B<sub>IM</sub> shows substantial departure from zero on yearly time scales (Figure 4e), highlighting unresolved variability of the carbon cycle, likely in the land sink (S<sub>LAND</sub>), given its large year to year variability (Figure 4d and 8).

Both the budget imbalance (B<sub>IM</sub>, Table 7) and the residual land sink from the global budget (E<sub>FOS</sub>+E<sub>LUC</sub>-GATM-SOCEAN, Table 5) include an error term due to the inconsistencies that arises from combining E<sub>LUC</sub> from bookkeeping models with S<sub>LAND</sub> from DGVMs, most notably the loss of additional sink capacity (see Section 2.10 and Appendix D.4). Other differences include a better accounting of land use changes practices and processes in bookkeeping models than in DGVMs, or the bookkeeping models error of having present-day observed carbon densities fixed in the past. That the budget imbalance shows no clear trend towards larger values over time is an indication that these inconsistencies probably play a minor role compared to other errors in S<sub>LAND</sub> or S<sub>OCEAN</sub>.

Although the budget imbalance is near zero for the recent decades, it could be due to a compensation of errors. We cannot exclude an overestimation of CO<sub>2</sub> emissions, particularly from land-use change, given their large

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uncertainty, as has been suggested elsewhere (Piao et al., 2018), combined with an underestimate of the sinks. A larger DGVM (SLAND-ELUC) over the extra-tropics would reconcile model results with inversion estimates for fluxes in the total land during the past decade (Figure 13; Table 5). Likewise, a larger SOCEAN is also possible given the higher estimates from the  $\text{CO}_2$ -products (see Section 3.6.2, Figure 10 and Figure 13), the underestimation of interior ocean anthropogenic carbon accumulation in the GOBMs (Section 3.6.5), and the recently suggested upward adjustments of the ocean carbon sink in Earth System Models (Terhaar et al., 2022), and in  $\text{CO}_2$ -products, here related to a potential temperature bias and skin effects (Watson et al., 2020; Dong et al., 2022; Figure 10). If SOCEAN were to be based on  $\text{CO}_2$ -products alone, with all  $\text{CO}_2$ -products including this adjustment, this would result in a 2013-2022 SOCEAN of  $3.7 \text{ GtC yr}^{-1}$  (Dong et al., 2022) or  $>3.9 \text{ GtC yr}^{-1}$  (Watson et al., 2020), i.e., outside of the range supported by the atmospheric inversions and with an implied negative  $B_{\text{IM}}$  of more than  $-1 \text{ GtC yr}^{-1}$  indicating that a closure of the budget could only be achieved with either anthropogenic emissions being significantly larger and/or the net land sink being substantially smaller than estimated here. A recent model study suggests that the skin effect is smaller (about  $0.1 \text{ GtC yr}^{-1}$  or 5%) due to feedbacks with surface carbon concentration (Bellenger et al., 2023), which would nevertheless lead to a larger SOCEAN even in the GOBMs. More integrated use of observations in the Global Carbon Budget, either on their own or for further constraining model results, should help resolve some of the budget imbalance (Peters et al., 2017).

#### 4 Tracking progress towards mitigation targets

The average growth in global fossil  $\text{CO}_2$  emissions peaked at nearly +3% per year during the 2000s, driven by the rapid growth in emissions in China. In the last decade, however, the global growth rate has slowly declined, reaching a low +0.5% per year over 2013-2022. While this slowdown in global fossil  $\text{CO}_2$  emissions growth is welcome, global fossil  $\text{CO}_2$  emissions continue to grow, far from the rapid emission decreases needed to be consistent with the temperature goals of the Paris Agreement.

Since the 1990s, the average growth rate of fossil  $\text{CO}_2$  emissions has continuously declined across the group of developed countries of the Organisation for Economic Co-operation and Development (OECD), with emissions peaking in around 2005 and now declining at around  $1\% \text{ yr}^{-1}$  (Le Quéré et al., 2021). In the decade 2013-2022, territorial fossil  $\text{CO}_2$  emissions decreased significantly (at the 95% confidence level) in 18 countries/economies whose economies grew significantly (also at the 95% confidence level): Belgium, Brazil, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hong Kong, Israel, Italy, Jamaica, Japan, Luxembourg, Netherlands, Norway, Portugal, Romania, Slovenia, South Africa, Sweden, Switzerland, United Kingdom, USA, Zimbabwe (updated from Le Quéré et al., 2019). Altogether, these 18 countries emitted  $1.9 \text{ GtC yr}^{-1}$  ( $7.1 \text{ GtCO}_2 \text{ yr}^{-1}$ ) on average over the last decade, about 20% of world  $\text{CO}_2$  fossil emissions. Figure 16 shows that the emission declines in the USA and the EU27 are primarily driven by slightly weaker economic growth in the last decade compared to the 1990s, sustained declines in energy per GDP (though, weakening in the USA), and sustained declines in  $\text{CO}_2$  emissions per unit energy (decarbonisation) with a slight acceleration in the US in the last decade.

In contrast, fossil  $\text{CO}_2$  emissions continue to grow in non-OECD countries, although the growth rate has slowed from almost  $6\% \text{ yr}^{-1}$  during the 2000s to less than  $2\% \text{ yr}^{-1}$  in the last decade. Representing 47% of non-OECD

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emissions in 2022, a large part of this slowdown is due to China, which has seen emissions growth decline from 9% yr<sup>-1</sup> in the 2000s to 2.2% yr<sup>-1</sup> in the last decade. Excluding China, non-OECD emissions grew at 3.1% yr<sup>-1</sup> in the 2000s compared to 1.5% yr<sup>-1</sup> in the last decade. Figure 16 shows that China has had weaker economic growth in the 2000s compared to the 2010s and a higher decarbonisation rate, from 2005 to 2015 comparable to the highs in the 1990s, though the decarbonisation rate has slowed considerably since 2016. India and the rest of the world have strong economic growth that is not offset by decarbonisation or declines in energy per GDP, driving up fossil CO<sub>2</sub> emissions. Despite the high deployment of renewables in some countries (e.g., India), fossil energy sources continue to grow to meet growing energy demand (Le Quéré et al., 2019).

Globally, fossil CO<sub>2</sub> emissions growth is slowing, and this is due in part to the emergence of climate policy (Eskander and Fankhauser 2020; Le Quere et al 2019) and technological change, which is leading to a shift from coal to gas and growth in renewable energies, and reduced expansion of coal capacity. At the aggregated global level, decarbonisation shows a strong and growing signal in the last decade, with smaller contributions from lower economic growth and declines in energy per GDP. Despite the slowing growth in global fossil CO<sub>2</sub> emissions, emissions are still growing, far from the reductions needed to meet the ambitious climate goals of the UNFCCC Paris agreement.

This year we updated the remaining carbon budget (RCB) based on two studies, the IPCC AR6 (Canadell et al., 2021) as used in GCB2022, and a recent revision of the IPCC AR6 estimates (Forster et al 2023). We update the RCB assessed by the IPCC AR6 (Canadell et al., 2021), accounting for the 2020 to 2023 estimated emissions from fossil fuel combustion (E<sub>FOS</sub>) and land use changes (E<sub>LUC</sub>). From January 2024, the IPCC AR6 RCB (50% likelihood) for limiting global warming to 1.5°C, 1.7°C and 2°C is estimated to amount to 95, 190, and 325 GtC (340, 690, 1190 GtCO<sub>2</sub>). The Forster et al. (2023) study proposed a significantly lower RCB than IPCC AR6, with the largest reduction being due to an update of the climate emulator (MAGICC) used to estimate the warming contribution of non-CO<sub>2</sub> agents, and to the warming (i.e. emissions) that occurred over the 2020-2022 period. We update the Forster et al., budget accounting for the 2023 estimated emissions from fossil fuel combustion (E<sub>FOS</sub>) and land use changes (E<sub>LUC</sub>). From January 2024, the Forster et al., (2023) RCB (50% likelihood) for limiting global warming to 1.5°C, 1.7°C and 2°C is estimated to amount to 55, 155, and 305 GtC (210, 560, 1110 GtCO<sub>2</sub>), significantly smaller than the updated IPCC AR6 estimate. Both the original IPCC AR6 and Forster et al. (2023) estimates include an uncertainty due to the climate response to cumulative CO<sub>2</sub> emissions, which is reflected through the percent likelihood of exceeding the given temperature threshold, an additional uncertainty of 220GtCO<sub>2</sub> due to alternative non-CO<sub>2</sub> emission scenarios, and other sources of uncertainties (see Canadell et al., 2021). The two sets of estimates overlap when considering all uncertainties. The IPCC AR6 estimates have the advantage of a consensus building approach, while the Forster et al. (2023) estimates include significant update estimates but without the backing of the IPCC yet. Here, we take the average of our update of both IPCC AR6 and Forster et al. (2023) estimates, giving a remaining carbon (50% likelihood) for limiting global warming to 1.5°C, 1.7°C and 2°C of respectively 75, 175, and 315 GtC (275, 625, 1150 GtCO<sub>2</sub>) starting from January 2024. We emphasise the large uncertainties, particularly when close to the global warming limit of 1.5°C. These 1.5°C, 1.7°C and 2°C average remaining carbon budgets correspond respectively to about 7, 15 and 28 years from the beginning of 2024, at the 2023 level of total anthropogenic CO<sub>2</sub> emissions. Reaching net-zero CO<sub>2</sub> emissions by 2050 entails cutting total anthropogenic CO<sub>2</sub> emissions by

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about 0.4 GtC (1.5 GtCO<sub>2</sub>) each year on average, comparable to the decrease in E<sub>FOS</sub> observed in 2020 during the COVID-19 pandemic. However, this would lead to cumulative emissions over 2024-2050 of 150 GtC (550 GtCO<sub>2</sub>), well above the remaining carbon budget of 75 GtC to limit global warming to 1.5°C, but still below the remaining budget of 175 GtC to limit warming to 1.7°C (in phase with the “well below 2°C” ambition of the Paris Agreement). Even reaching net zero CO<sub>2</sub> globally by 2040, which would require annual emissions cuts of 0.7 GtC (2.4 GtCO<sub>2</sub>) on average, would still exceed the remaining carbon budget, with 95 GtC (350 GtCO<sub>2</sub>) cumulative emissions over 2024-2050, unless the global emissions trajectory becomes net negative (i.e. more anthropogenic CO<sub>2</sub> sinks than emissions) after 2040.

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## 5 Discussion

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Each year when the global carbon budget is published, each flux component is updated for all previous years to consider corrections that are the result of further scrutiny and verification of the underlying data in the primary input data sets. Annual estimates may be updated with improvements in data quality and timeliness (e.g., to eliminate the need for extrapolation of forcing data such as land-use). Of all terms in the global budget, only the fossil CO<sub>2</sub> emissions and the growth rate in atmospheric CO<sub>2</sub> concentration are based primarily on empirical inputs supporting annual estimates in this carbon budget. The carbon budget imbalance, yet an imperfect measure, provides a strong indication of the limitations in observations, in understanding and representing processes in models, and/or in the integration of the carbon budget components.

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The persistent unexplained variability in the carbon budget imbalance limits our ability to verify reported emissions (Peters et al., 2017) and suggests we do not yet have a complete understanding of the underlying carbon cycle dynamics on annual to decadal timescales. Resolving most of this unexplained variability should be possible through different and complementary approaches. First, as intended with our annual updates, the imbalance as an error term should be reduced by improvements of individual components of the global carbon budget that follow from improving the underlying data and statistics and by improving the models through the resolution of some of the key uncertainties detailed in Table 10. Second, additional clues to the origin and processes responsible for the variability in the budget imbalance could be obtained through a closer scrutiny of carbon variability in light of other Earth system data (e.g., heat balance, water balance), and the use of a wider range of biogeochemical observations to better understand the land-ocean partitioning of the carbon imbalance such as the constraint from atmospheric oxygen included this year. Finally, additional information could also be obtained through better inclusion of process knowledge at the regional level, and through the introduction of inferred fluxes such as those based on satellite xCO<sub>2</sub> retrievals. The limit of the resolution of the carbon budget imbalance is yet unclear, but most certainly not yet reached given the possibilities for improvements that lie ahead.

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Estimates of global fossil CO<sub>2</sub> emissions from different datasets are in relatively good agreement when the different system boundaries of these datasets are considered (Andrew, 2020a). But while estimates of E<sub>FOS</sub> are derived from reported activity data requiring much fewer complex transformations than some other components of the budget, uncertainties remain, and one reason for the apparently low variation between datasets is precisely the reliance on the same underlying reported energy data. The budget excludes some sources of fossil CO<sub>2</sub> emissions, which available evidence suggests are relatively small (<1%). We have added emissions from lime

4209 production in China and the US, but these are still absent in most other non-Annex I countries, and before 1990  
4210 in other Annex I countries.

4211 Estimates of  $E_{LUC}$  suffer from a range of intertwined issues, including the poor quality of historical land-cover  
4212 and land-use change maps, the rudimentary representation of management processes in most models, and the  
4213 confusion in methodologies and boundary conditions used across methods (e.g., Arneth et al., 2017; Pongratz et  
4214 al., 2014, see also Appendix D.4 on the loss of sink capacity; Bastos et al., 2021). Uncertainties in current and  
4215 historical carbon stocks in soils and vegetation also add uncertainty in the  $E_{LUC}$  estimates. Unless a major effort  
4216 to resolve these issues is made, little progress is expected in the resolution of  $E_{LUC}$ . This is particularly  
4217 concerning given the growing importance of  $E_{LUC}$  for climate mitigation strategies, and the large issues in the  
4218 quantification of the cumulative emissions over the historical period that arise from large uncertainties in  $E_{LUC}$ .

4219 By adding the DGVMs estimates of  $CO_2$  fluxes due to environmental change from countries' managed forest  
4220 areas (part of  $S_{LAND}$  in this budget) to the budget  $E_{LUC}$  estimate, we successfully reconciled the large gap  
4221 between our  $E_{LUC}$  estimate and the land use flux from NGHGs using the approach described in Grassi et al.  
4222 (2021) for future [scenarios](#) and in Grassi et al. (2023) using data from the Global Carbon Budget 2021. The  
4223 updated data presented here can be used as potential adjustment in the policy context, e.g., to help [assess](#) the  
4224 collective countries' progress towards the goal of the Paris Agreement and avoiding double-accounting for the  
4225 sink in managed forests. In the absence of this adjustment, collective progress would hence appear better than it  
4226 is (Grassi et al., 2021). The [application of this adjustment is also recommended in the UNFCCC Synthesis](#)  
4227 [report for the first Global Stocktake \(UNFCCC, 2022\)](#) whenever a comparison between LULUCF fluxes  
4228 reported by countries and the global emission estimates of the IPCC is [conducted](#). However, this adjustment  
4229 should be seen as a short-term and pragmatic fix based on existing data, rather than a definitive solution to  
4230 bridge the differences between global models and national inventories. Additional steps are needed to  
4231 understand and reconcile the remaining differences, some of which are relevant at the country level (Grassi, et  
4232 al., 2023, Schwingshackl, et al., 2022).

4233 The comparison of GOBMs,  $fCO_2$ -products, and inversions highlights substantial discrepancy in the [temporal](#)  
4234 [evolution of  \$SO\_{CEAN}\$  in the Southern Ocean and northern high-latitudes](#) (Figure 13, Hauck et al., 2023) and in the  
4235 [mean  \$SO\_{CEAN}\$  in the tropics](#). A large part of the uncertainty in the mean fluxes stems from the regional  
4236 distribution of the river flux adjustment term. The current distribution [simulates the largest share of the](#)  
4237 [outgassing to occur in the tropics \(Lacroix et al., 2020\) in contrast to the regional distribution previously used](#)  
4238 [with the largest riverine outgassing flux south of 20°S \(Aumont et al., 2001\)](#). The long-standing sparse data  
4239 coverage of  $fCO_2$  observations in the Southern compared to the Northern Hemisphere (e.g., Takahashi et al.,  
4240 2009) continues to exist (Bakker et al., 2016, 2022, Figure B1) and to lead to substantially higher uncertainty in  
4241 the  $SO_{CEAN}$  estimate for the Southern Hemisphere (Watson et al., 2020, Gloege et al., 2021, [Hauck et al., 2023](#)).  
4242 This discrepancy, which also hampers model improvement, points to the need for increased high-quality  $fCO_2$   
4243 observations especially in the Southern Ocean. At the same time, model uncertainty is illustrated by the large  
4244 spread of individual GOBM estimates (indicated by shading in Figure 13) and highlights the need for model  
4245 improvement. The diverging trends in  $SO_{CEAN}$  from different methods is a matter of concern. [Recent and on-](#)  
4246 [going work suggests that the  \$fCO\_2\$ -products may overestimate the trend \(Hauck et al., 2023\), though many](#)  
4247 [products remain to be tested, whereas evidence is accumulating that GOBMs likely underestimate the mean flux](#)

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(Section 3.6.2, Terhaar et al., 2022, DeVries et al., 2023, Müller et al., 2023). The independent constraint from atmospheric oxygen measurements is consistent within errors with the relatively larger ocean sink in the  $fCO_2$ -products. The assessment of the net land-atmosphere exchange from DGVMs and atmospheric inversions also shows substantial discrepancy, particularly for the estimate of the net land flux over the northern extra-tropic. This discrepancy highlights the difficulty to quantify complex processes (CO<sub>2</sub> fertilisation, nitrogen deposition and fertilisers, climate change and variability, land management, etc.) that collectively determine the net land CO<sub>2</sub> flux. Resolving the differences in the Northern Hemisphere land sink will require the consideration and inclusion of larger volumes of observations.

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We provide metrics for the evaluation of the ocean and land models and the atmospheric inversions (Figures B2 to B4, Table A10). These metrics expand the use of observations in the global carbon budget, helping 1) to support improvements in the ocean and land carbon models that produce the sink estimates, and 2) to constrain the representation of key underlying processes in the models and to allocate the regional partitioning of the CO<sub>2</sub> fluxes. The introduction of process-based metrics targeted to evaluate the simulation of SOCEAN in the ocean biogeochemistry models is an important addition to the evaluation based on ocean carbon observations. This is an initial step towards the introduction of a broader range of observations and more stringent model evaluation that we hope will support continued improvements in the annual estimates of the global carbon budget.

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We assessed before that a sustained decrease of –1% in global emissions could be detected at the 66% likelihood level after a decade only (Peters et al., 2017). Similarly, a change in behaviour of the land and/or ocean carbon sink would take as long to detect, and much longer if it emerges more slowly. To continue reducing the carbon imbalance on annual to decadal time scales, regionalising the carbon budget, and integrating multiple variables are powerful ways to shorten the detection limit and ensure the research community can rapidly identify issues of concern in the evolution of the global carbon cycle under the current rapid and unprecedented changing environmental conditions.

## 6 Conclusions

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The estimation of global CO<sub>2</sub> emissions and sinks is a major effort by the carbon cycle research community that requires a careful compilation and synthesis of measurements, statistical estimates, and model results. The delivery of an annual carbon budget serves two purposes. First, there is a large demand for up-to-date information on the state of the anthropogenic perturbation of the climate system and its underpinning causes. A broad stakeholder community relies on the data sets associated with the annual carbon budget including scientists, policy makers, businesses, journalists, and non-governmental organisations engaged in adapting to and mitigating human-driven climate change. Second, over the last decades we have seen unprecedented changes in the human and biophysical environments (e.g., changes in the growth of fossil fuel emissions, impact of COVID-19 pandemic, Earth's warming, and strength of the carbon sinks), which call for frequent assessments of the state of the planet, a better quantification of the causes of changes in the contemporary global carbon cycle, and an improved capacity to anticipate its evolution in the future. Building this scientific understanding to meet the extraordinary climate mitigation challenge requires frequent, robust, transparent, and traceable data sets and methods that can be scrutinised and replicated. This paper via 'living data' helps to keep track of new budget updates.

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4315 **Data availability**

4316 The data presented here are made available in the belief that their wide dissemination will lead to greater  
4317 understanding and new scientific insights of how the carbon cycle works, how humans are altering it, and how  
4318 we can mitigate the resulting human-driven climate change. Full contact details and information on how to cite  
4319 the data shown here are given at the top of each page in the accompanying database and summarised in Table 2.

4320 The accompanying database includes three Excel files organised in the following spreadsheets:

4321 File [Global Carbon Budget 2023v0.1.xlsx](#) includes the following:

- 4322 1. Summary
- 4323 2. The global carbon budget (1959-[2022](#));
- 4324 3. The historical global carbon budget (1750-[2022](#));
- 4325 4. Global CO<sub>2</sub> emissions from fossil fuels and cement production by fuel type, and the per-capita emissions  
4326 (1850-[2022](#));
- 4327 5. CO<sub>2</sub> emissions from land-use change from the individual bookkeeping models (1959-[2022](#));
- 4328 6. Ocean CO<sub>2</sub> sink from the individual [global](#) ocean [biogeochemistry](#) models and [fCO<sub>2</sub>-products](#) (1959-  
4329 [2022](#));
- 4330 7. Terrestrial CO<sub>2</sub> sink from the individual DGVMs (1959-[2022](#));
- 4331 8. Cement carbonation CO<sub>2</sub> sink (1959-[2022](#)).

4332 File [National Fossil Carbon Emissions 2023v0.1.xlsx](#) includes the following:

- 4333 1. Summary
- 4334 2. Territorial country CO<sub>2</sub> emissions from fossil fuels and cement production (1850-[2022](#));
- 4335 3. Consumption country CO<sub>2</sub> emissions from fossil fuels and cement production and emissions transfer from  
4336 the international trade of goods and services (1990-2020) using CDIAC/UNFCCC data as reference;
- 4337 4. Emissions transfers (Consumption minus territorial emissions; 1990-2020);
- 4338 5. Country definitions.

4339 File [National LandUseChange Carbon Emissions 2023v0.1.xlsx](#) includes the following:

- 4340 1. Summary
- 4341 2. Territorial country CO<sub>2</sub> emissions from Land Use Change (1850-[2022](#)) from three bookkeeping models;

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4356 All three spreadsheets are published by the Integrated Carbon Observation System (ICOS) Carbon Portal and  
 4357 are available at <https://doi.org/10.18160/GCP-2023> (Friedlingstein et al., 2023). National emissions data are also  
 4358 available on Zenodo (Andrew and Peters, 2022), from the Global Carbon Atlas  
 4359 (<http://www.globalcarbonatlas.org/>, last access: 27 September 2023) and from Our World in Data  
 4360 (<https://ourworldindata.org/co2-emissions>, last access: 27 September 2023).

#### 4361 Author contributions

4362 PF, MO, MWJ, RMA, DCEB, JH, PL, CLQ, ITL, GPP, WP, JP, CSc, and SSi designed the study, conducted the  
 4363 analysis, and wrote the paper with input from JGC, PCi and RBJ. RMA, GPP and JIK produced the fossil CO<sub>2</sub>  
 4364 emissions and their uncertainties and analysed the emissions data. MH and GMa provided fossil fuel emission  
 4365 data. JP, TGA, CSc and RAH provided the bookkeeping land-use change emissions with synthesis by JP and  
 4366 CSc. FJo provided peat drainage emission estimates. SSm and CMP provided the estimates of non-vegetation  
 4367 CDR fluxes. LBo, MCh, ÖG, NG, TI, TJ, LR, JS, RS, and HiT, provided an update of the global ocean  
 4368 biogeochemical models. TTTC, DF, LG, YI, AJ, GMe, ChR, and JZ provided an update of the ocean fCO<sub>2</sub> data  
 4369 products, with synthesis on both streams by JH, PL and NMa. SRA, LBA, NRB, MB, MCr, KE, WE, RAF, TGK,  
 4370 AK, NL, DRM, SN, AO, AMO, TO, MEP, DP, KP, GR, AJS, CSw, ST, BT, EVO, RW, and CWR provided  
 4371 ocean fCO<sub>2</sub> measurements for the year 2022, with synthesis by DCEB and KMO. PA, DB, SF, JG, HJ, AKJ,  
 4372 EK, DK, JK, GMe, LM, PM, MO, BP, TLS, QS, HTi, WY, XYua, XYue, and SZ provided an update of the  
 4373 Dynamic Global Vegetation Models, with synthesis by SSi and MO. HL, RSA, MW, and PCa provided  
 4374 estimates of land and ocean sinks from Earth System Models, as well as a projection of the atmospheric growth  
 4375 rate for 2023. FC, ITL, NC, LF, ARJ, FJi, JL, ZJin, ZLiu, YN, CR, DY, and BZ provided an updated  
 4376 atmospheric inversion, WP, FC, and ITL developed the protocol and produced the synthesis and evaluation of  
 4377 the atmospheric inversions. RMA provided projections of the 2023 fossil emissions and atmospheric CO<sub>2</sub>  
 4378 growth rate. PL provided the predictions of the 2023 ocean and land sinks. IBMB, LPC, GCH, KKG, TMR, and  
 4379 GRvdW provided forcing data for land-use change. FT and GG provided data for the land-use change NGHGI  
 4380 harmonisation. RK provided key atmospheric CO<sub>2</sub> data. EJM and RFK provided the atmospheric oxygen  
 4381 constraint on surface net carbon sinks. XL, PPT and MWJ provided the historical atmospheric CO<sub>2</sub>  
 4382 concentration and growth rate. MO and NB produced the aerosol diffuse radiative forcing for the DGVMs. IH  
 4383 provided the climate forcing data for the DGVMs. ER provided the evaluation of the DGVMs. MWJ provided  
 4384 the emissions prior for use in the inversion systems. XD provided seasonal emissions data for most recent years  
 4385 for the emission prior. PF, MO and MWJ coordinated the effort, revised all figures, tables, text and numbers to  
 4386 ensure the update was clear from the 2022 edition and in line with the globalcarbonatlas.org.

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[103]

**Competing interests.**

The authors declare that they have no conflict of interest.

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7933 **Tables**

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Unit 1	Unit 2	Conversion	Source
GtC (gigatonnes of carbon)	ppm (parts per million) (a)	2.124 (b)	Ballantyne et al. (2012)
GtC (gigatonnes of carbon)	PgC (petagrams of carbon)	1	SI unit conversion
GtCO <sub>2</sub> (gigatonnes of carbon dioxide)	GtC (gigatonnes of carbon)	3.664	44.01/12.011 in mass equivalent
GtC (gigatonnes of carbon)	MtC (megatonnes of carbon)	1000	SI unit conversion
(a) Measurements of atmospheric CO <sub>2</sub> concentration have units of dry-air mole fraction. 'ppm' is an abbreviation for micromole/mol, dry air.			
(b) The use of a factor of 2.124 assumes that all the atmosphere is well mixed within one year. In reality, only the troposphere is well mixed and the growth rate of CO <sub>2</sub> concentration in the less well-mixed stratosphere is not measured by sites from the NOAA network. Using a factor of 2.124 makes the approximation that the growth rate of CO <sub>2</sub> concentration in the stratosphere equals that of the troposphere on a yearly basis.			

7936 **Table 1.** Factors used to convert carbon in various units (by convention, Unit 1 = Unit 2 × conversion).

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Component	Primary reference
Global fossil CO2 emissions (EFOS), total and by fuel type	Updated from Andrew and Peters (2022)
National territorial fossil CO2 emissions (EFOS)	Gillfillan and Marland (2021), UNFCCC (2022)
National consumption-based fossil CO2 emissions (EFOS) by country (consumption)	Peters et al. (2011a) updated as described in this paper
Net land-use change flux (ELUC)	This paper (see Table 4 for individual model references)
Growth rate in atmospheric CO2 concentration (GATM)	Lan et al. (2023)
Ocean and land CO2 sinks (SOCEAN and SLAND)	This paper (see Table 4 for individual model and data products references)

Table 2. How to cite the individual components of the global carbon budget presented here.

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Publication year	Fossil fuel emissions		LUC emissions	Reservoirs			Other changes
	Global	Country (territorial)		Atmosphere	Ocean	Land	
2019	Global emissions calculated as sum of all countries plus bunkers, rather than taken directly from CDIAC.		Average of two bookkeeping models; use of 15 DGVMs	Use of three atmospheric inversions	Based on nine models	Based on 16 models	
Friedlingstein et al. (2019) GCB2019							
2020		India's emissions from Andrew (2020: India); Corrections to Netherland Antilles and Aruba and Soviet emissions before 1950 as per Andrew (2020: CO <sub>2</sub> ); China's coal emissions in 2019 derived from official statistics, emissions now shown for EU27 instead of EU28. Projection for 2020 based on assessment of four approaches	Average of three bookkeeping models; use of 17 DGVMs. Estimate of gross land use sources and sinks provided	Use of six atmospheric inversions	Based on nine models. River flux revised and partitioned NH, Tropics, SH	Based on 17 models	
Friedlingstein et al. (2020) GCB2020							
2021	Projections are no longer an assessment of four approaches.	Official data included for a number of additional countries, new estimates for South Korea, added emissions from lime	ELUC estimate compared to the estimates adopted in national GHG inventories (NGHGI)		Average of means of eight models and means of seven data-products. Current year prediction of SOCEAN using a feed-forward	Current year prediction of SLAND using a feed-forward neural network method	
Friedlingstein et al. (2022a) GCB2021							

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		production in China.			neural network method.		
2022			ELUC provided at country level. <a href="#">Revised components decomposition of ELUC</a> fluxes. <a href="#">Revision of</a> LUC maps for Brazil. <a href="#">New</a> datasets for peat drainage.	Use of nine atmospheric inversions.	Average of means of ten models and means of seven data-products.	Based on 16 models. <a href="#">Revision of</a> LUC maps for Brazil.	
<a href="#">Friedlingstein et al. (2022) GCB2022</a>							
2023			<a href="#">Refined components decomposition of ELUC.</a> <a href="#">Revision of</a> LUC maps for Indonesia. Use of updated peat drainage estimates.	<a href="#">Use of 14 atmospheric inversions.</a> <a href="#">Additional use of 4 Earth System Models to estimate current year CO2</a>	<a href="#">Additional use of 4 Earth System Models and atmospheric oxygen method to assess SOCEAN.</a> <a href="#">Regional distribution of river flux adjustment revised.</a>	<a href="#">Based on 20 models.</a> <a href="#">Additional use of 4 Earth System Models and atmospheric oxygen method to assess the net atmosphere-land flux.</a>	<a href="#">Inclusion of an estimate of Carbon Dioxide Removal (CDR)</a>
<a href="#">This study</a>							

**Table 3.** Main methodological changes in the global carbon budget since 2019. Methodological changes introduced in one year are kept for the following years unless noted. Empty cells mean there were no methodological changes introduced that year. Table A8 lists methodological changes from the first global carbon budget publication up to 2018.

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Model/data name	Reference	Change from Global Carbon Budget 2022 (Friedlingstein et al., 2022b)
<b>Bookkeeping models for land-use change emissions</b>		
BLUE	Hansis et al. (2015)	No change to model, but simulations performed with LUH2-GCB2023 forcing. Update in added peat drainage emissions.
H&C2023	Houghton and Castanho (2023)	H&C2023 replaces the formerly used H&N2017 model. Minor bug fix in fuel harvest estimates. Update in added peat drainage emissions.
OSCAR	Gasser et al. (2020)	No change to model, but land-use forcing changed to LUH2-GCB2023 and FRA2020 (extrapolated to 2022). Constraining based on GCB2022 data for SLAND over 1960-2021. Update in added peat drainage emissions.
<b>Dynamic global vegetation models</b>		
CABLE-POP	Haverd et al. (2018)	Improved representation of nitrogen retranslocation and plant uptake, minor bug fixes, parameter changes.
CLASSIC	Melton et al. (2020), Asaadi et al. (2018)	Bug fixes, correct allocation of leaves after summer solstice for latitudes higher than 45°N, improved phenology for several PFTs.
CLM5.0	Lawrence et al. (2019)	No change.
DLEM	Tian et al. (2011, 2015)	No change.
EDv3	Moorcroft et al. (2001), Ma et al. (2022)	New this year.
ELM	Yang et al. (2023), Burrows et al. (2020)	New this year.

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		and prior fluxes.
CAMS-Satellite	Chevallier et al. (2005), Remaud et al. (2018)	Increase of the 3D resolution, extension to year 2022 and the first months of 2023; removal of the pre-OCO-2 period (2010-2014 with GOSAT); update of the prior fluxes.
GONGGA	Jin et al. (2023)	Update of OCO-2 observations and prior fluxes.
THU	Kong et al. (2022)	Updates to the OCO-2 product and the fossil fuel data.
COLA	Liu et al. (2022)	New this year.
GCASv2	Jiang et al. (2021, 2022)	New this year.
UoE in-situ	Feng et al. (2009), Feng et al. (2016), Palmer et al. (2019)	Update of the inversion system by using new version of GEOS-Chem
IAPCAS	Feng et al. (2016), Yang et al. (2021)	New this year.
MIROC4-ACTM	Chandra et al. (2022)	New this year
<b>Earth System Models</b>		
CanESM5	Swart et al. (2019), Sospedra-Alfonso et al. (2021)	New this year.
JPSL-CM6a-CO2-LR	Boucher et al. (2020)	New this year.
MIROC-ES2L	Watanabe et al. (2020)	New this year.
MPI-ESM1-2-LR	Mauritsen et al. (2019), Li et al. (2023)	New this year.

**Table 4.** References for the process models, bookkeeping models, ocean data products, and atmospheric inversions. All models and products are updated with new data to the end of year 2022, and the atmospheric forcing for the DGVMs has been updated as described in Section C.2.2 and C.4.1.

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		1960s	1970s	1980s	1990s	2000s	2013-2022	2022
Land-use change emissions (ELUC)	Bookkeeping (BK) Net flux (1a)	1.5±0.7	1.3±0.7	1.4±0.7	1.6±0.7	1.4±0.7	1.3±0.7	1.2±0.7
	BK - deforestation (total)	1.7 [1.3,2.1]	1.6 [1.2,1.9]	1.7 [1.3,2.1]	1.9 [1.6,2.2]	2 [1.6,2.4]	1.9 [1.5,2.4]	1.9 [1.4,2.5]
	BK - forest regrowth (total)	-0.8 [-1.1,-0.6]	-0.9 [-1.1,-0.7]	-0.9 [-1.1,-0.7]	-1 [-1.2,-0.7]	-1.1 [-1.3,-0.8]	-1.3 [-1.5,-0.9]	-1.3 [-1.6,-1]
	BK - other transitions	0.4 [0.3,0.4]	0.2 [0.1,0.3]	0.2 [0.2,0.3]	0.1 [0,0.2]	0.1 [0,0.2]	0.1 [0,0.3]	0.1 [0,0.2]
	BK - peat drainage & peat fires	0.2 [0.1,0.2]	0.2 [0.1,0.2]	0.2 [0.2,0.3]	0.3 [0.3,0.3]	0.3 [0.2,0.3]	0.3 [0.3,0.3]	0.2 [0.2,0.3]
	BK - wood harvest & forest management	0.2 [-0.2,0.6]	0.2 [-0.2,0.6]	0.2 [-0.2,0.6]	0.2 [-0.1,0.6]	0.2 [-0.1,0.6]	0.2 [0,0.6]	0.2 [0,0.7]
	DGVMS-net flux (1b)	1.5±0.5	1.3±0.5	1.6±0.6	1.8±0.6	1.8±0.7	1.7±0.6	1.7±0.6
Terrestrial sink (SLAND)	Residual sink from global budget ( $E_{FOS} + E_{ELUC}(1a) - G_{ATM} - S_{OCEAN}$ ) (2a)	1.7±0.8	1.8±0.8	1.7±0.9	2.7±0.9	2.9±0.9	2.9±0.9	3.7±1
	DGVMS (2b)	1.3±0.5	2±0.7	1.9±0.8	2.5±0.6	2.9±0.7	3.3±0.8	3.8±0.8
Net land fluxes (SLAND-ELUC)	GCB2023 Budget (2b-1a)	-0.2±0.8	0.8±1	0.5±1	0.9±0.9	1.4±1	2.1±1.1	2.6±1.1
	Atmospheric O <sub>2</sub>	---	---	---	1.2±1	1.1±1.1	1.1±1.3	-
	DGVMS-net (2b-1b)	-0.2±0.4	0.7±0.7	0.3±0.6	0.7±0.5	1.1±0.4	1.7±0.6	2.1±0.6
	Inversions*	- [-,-]	- [-,-]	0.5 [0.4,0.6] (2)	0.9 [0.6,1.3] (3)	1.3 [0.7,2] (4)	1.6 [0.5,2.3] (8)	2.7 [1.4-3.8] (13)
	ESMs	---	---	0.6 [0.1,1]	1.7 [1.3,2]	2 [1.4,2.7]	2.4 [1.8,3.3]	3.9 [2.8-5.5]

\*Estimates are adjusted for the pre-industrial influence of river fluxes, for the cement carbonation sink, and adjusted to common  $E_{FOS}$  (Sect. 2.7). The ranges given include varying numbers (in parentheses) of inversions in each decade (Table A4).

**Table 5.** Comparison of results from the bookkeeping method and budget residuals with results from the DGVMS, as well as additional estimates from atmospheric oxygen, atmospheric inversions and Earth System Models (ESMs) for different periods, the last decade, and the last year available. All values are in GtCyr<sup>-1</sup>. See Figure 7 for explanation of the bookkeeping component fluxes. The DGVM uncertainties represent  $\pm 1\sigma$  of the decadal or annual (for 2022) estimates from the individual DGVMs: for the inverse systems the mean and range of available results is given. All values are rounded to the nearest 0.1 GtC and therefore columns do not necessarily add to zero.

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Product	1960s	1970s	1980s	1990s	2000s	2013-2022	2022
fCO <sub>2</sub> -products	---	---	---	$\frac{2.3}{[2,2.9]}$	$\frac{2.4}{[2.2,2.7]}$	$\frac{3.1}{[2.6,3.3]}$	$\frac{3.1}{[2.5,3.3]}$
GOBMs	1±0.3	1.2±0.3	1.7±0.3	2±0.3	2.1±0.4	2.6±0.4	2.5±0.4
GCB2023 Budget	1.1±0.4	1.4±0.4	1.9±0.4	2.1±0.4	2.3±0.4	2.8±0.4	2.8±0.4
Atmospheric O <sub>2</sub>	---	---	---	2±0.7	2.6±0.6	3.3±0.6	-
Inversions	- [-,-]	- [-,-]	$\frac{1.7}{[1.6,1.8]}$ (2)	$\frac{2.2}{[1.9,2.5]}$ (3)	$\frac{2.4}{[1.8,3.1]}$ (4)	$\frac{3}{[2.4,4.1]}$ (8)	$\frac{3}{[2.2-4.2]}$ (13)
ESMs	---	---	$\frac{1.6}{[0.7,2.4]}$	$\frac{1.8}{[1.1,2.5]}$	$\frac{2.1}{[1.5,2.8]}$	$\frac{2.6}{[2.2,3.4]}$	$\frac{2.7}{[2.3-3.5]}$

**Table 6:** Comparison of results for the ocean sink from the fCO<sub>2</sub>-products, from global ocean biogeochemistry models (GOBMs), the best estimate for GCB2023 as calculated from fCO<sub>2</sub>-products and GOBMs that is used in the budget Table 7, as well as additional estimates from atmospheric oxygen, atmospheric inversions and Earth System Models (ESMs) for different periods, the last decade, and the last year available. All values are in GtCyr<sup>-1</sup>. Uncertainties represent ±1σ of the estimates from the GOBMs (N>10) and range of ensemble members is given for ensembles with N<10 (fCO<sub>2</sub>-products, inversions, ESMs). The uncertainty of the GCB2023 budget estimate is based on expert judgement (Section 2 and Appendix C) and for oxygen it is the standard deviation of a Monte Carlo ensemble (Section 2.8).

		1960s	1970s	1980s	1990s	2000s	2013-2022	2022	2023 (Projection)
Total emissions (EFOS + ELUC)	Fossil CO <sub>2</sub> emissions (EFOS) <sup>†</sup>	3±0.2	4.7±0.2	5.5±0.3	6.4±0.3	7.8±0.4	9.6±0.5	9.9±0.5	10±0.5
	Land-use change emissions (ELUC)	1.5±0.7	1.3±0.7	1.4±0.7	1.6±0.7	1.4±0.7	1.3±0.7	1.2±0.7	1.1±0.7
	Total emissions	4.6±0.7	6±0.7	6.9±0.8	7.9±0.8	9.2±0.8	10.9±0.8	11.1±0.9	11.2±0.9
Partitioning	Growth rate in atmos CO <sub>2</sub> (GATM)	1.7±0.07	2.8±0.07	3.4±0.02	3.1±0.02	4±0.02	5.2±0.02	4.6±0.2	4±0.4
	Ocean sink (SOCEAN)	1.1±0.4	1.4±0.4	1.9±0.4	2.1±0.4	2.3±0.4	2.8±0.4	2.8±0.4	2.9±0.4
	Terrestrial sink (SLAND)	1.3±0.5	2±0.7	1.9±0.8	2.5±0.6	2.9±0.7	3.3±0.8	3.8±0.8	3±1
Budget imbalance	BIM=EFOS+ELUC-(GATM+SOCEAN+SLAND)	0.4	-0.2	-0.2	0.2	0	-0.4	-0.1	1.2

<sup>†</sup>Fossil emissions excluding the cement carbonation sink amount to 3±0.2 GtC/yr, 4.7±0.2 GtC/yr, 5.5±0.3 GtC/yr, 6.4±0.3 GtC/yr, 7.9±0.4 GtC/yr, and 9.8±0.5 GtC/yr for the decades 1960s to 2010s respectively and to 10.2±0.5 GtC/yr for 2022, and 10.3±0.5 GtC/yr for 2023.

**Table 7:** Decadal mean in the five components of the anthropogenic CO<sub>2</sub> budget for different periods, and last year available. All values are in GtC yr<sup>-1</sup>, and uncertainties are reported as ±1σ. Fossil CO<sub>2</sub> emissions include cement carbonation. The table also shows the budget imbalance (B<sub>IM</sub>), which provides a measure of the discrepancies among the nearly independent estimates. A positive imbalance means the emissions are overestimated and/or the sinks are too small. All values are rounded to the nearest 0.1 GtC and therefore columns do not necessarily add to zero.

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		1750-2022	1850-2014	1850-2022	1960-2022	1850-2023
Emissions	Fossil CO <sub>2</sub> emissions (EFOS)	480±25	400±20	475±25	395±20	485±25
	Land-use change emissions (ELUC)	250±75	210±65	220±65	90±45	220±65
	Total emissions	730±80	610±65	695±70	485±50	705±70
Partitioning	Growth rate in atmos CO <sub>2</sub> (GATM)	300±5	235±5	280±5	215±5	280±5
	Ocean sink (SOCEAN)	190±40	155±30	180±35	125±25	180±35
	Terrestrial sink (SLAND)	245±60	200±50	225±55	150±35	225±55
Budget imbalance	BIM=EFOS+ELUC-(GATM+SOCEAN+SLAND)	-5	20	15	-5	15

**Table 8.** Cumulative CO<sub>2</sub> for different time periods in gigatonnes of carbon (GtC). Fossil CO<sub>2</sub> emissions include cement carbonation. The budget imbalance (B<sub>IM</sub>) provides a measure of the discrepancies among the nearly independent estimates. All values are rounded to the nearest 5 GtC and therefore columns do not necessarily add to zero. Uncertainties are reported as follows: EFOS is 5% of cumulative emissions; ELUC prior to 1959 is 1 $\sigma$  spread from the DGVMs, ELUC post-1959 is 0.7\*number of years (where 0.7 GtC/yr is the uncertainty on the annual ELUC flux estimate); GATM uncertainty is held constant at 5 GtC for all time periods; SOCEAN uncertainty is 20% of the cumulative sink (20% relates to the annual uncertainty of 0.4 GtC/yr, which is ~20% of the current ocean sink); and SLAND is the 1 $\sigma$  spread from the DGVMs estimates.

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	2003-2012	2013-2022
FLUC from bookkeeping estimates (from Table 5)	1.4	1.3
SLAND on non-intact forest from DGVMs	1.9	2.0
FLUC subtract SLAND on non-intact forests	-0.5	0.8
National Greenhouse Gas Inventories	-0.4	-0.7

**Table 9:** Translation of global carbon cycle models' land flux definitions to the definition of the LULUCF net flux used in national Greenhouse Gas Inventories reported to UNFCCC. See Sec. C.2.3 and Table A9 for detail on methodology and comparison to other datasets. Units are GtC yr<sup>-1</sup>.

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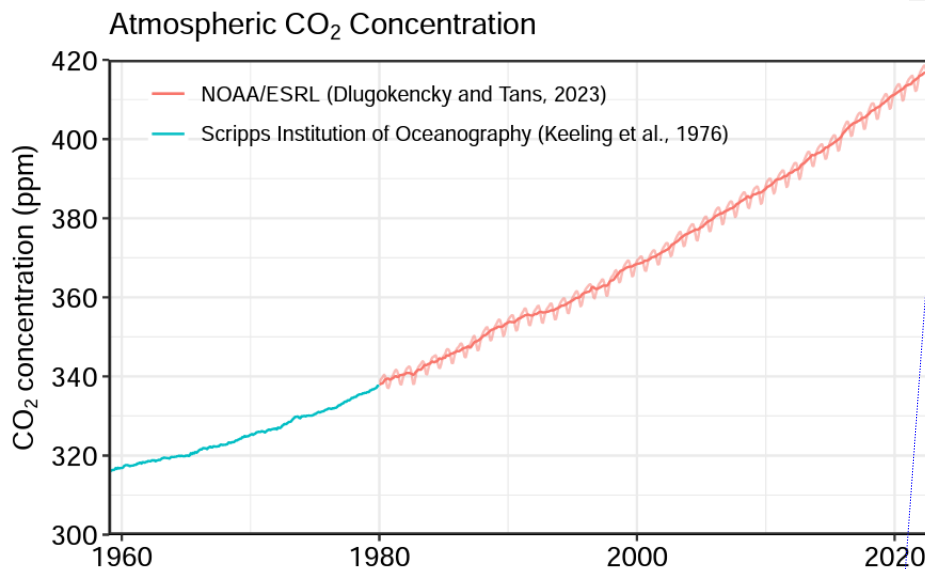
Source of uncertainty	Time scale (years)	Location	Evidence
Fossil CO <sub>2</sub> emissions (EFOS; Section 2.1)			
energy statistics	annual to decadal	global, but mainly China & major developing countries	(Korsbakken et al., 2016; Guan et al., 2012)
carbon content of coal	annual to decadal	global, but mainly China & major developing countries	(Liu et al., 2015)
system boundary	annual to decadal	all countries	(Andrew, 2020a)
Net land-use change flux (ELUC; section 2.2)			
land-cover and land-use change statistics	continuous	global; in particular tropics	(Houghton et al., 2012; Gasser et al., 2020; Ganzenmüller et al., 2022; Yu et al., 2022)
sub-grid-scale transitions	annual to decadal	global	(Wilkenskjeld et al., 2014)
vegetation biomass	annual to decadal	global; in particular tropics	(Houghton et al., 2012; Bastos et al., 2021)
forest degradation (fire, selective logging)	annual to decadal	tropics	(Aragão et al., 2018; Qin et al., 2021)
wood and crop harvest	annual to decadal	global; SE Asia	(Arneeth et al., 2017; Erb et al., 2018)
peat burning	multi-decadal trend	global	(van der Werf et al., 2010, 2017)
loss of additional sink capacity	multi-decadal trend	global	(Pongratz et al., 2014; Gasser et al., 2020; Obermeier et al., 2021)
Atmospheric growth rate (GATM; section 2.4) no demonstrated uncertainties larger than $\pm 0.3$ GtC yr <sup>-1</sup> . The uncertainties in GATM have been estimated as $\pm 0.2$ GtC yr <sup>-1</sup> , although the conversion of the growth rate into a global annual flux assuming instantaneous mixing throughout the atmosphere introduces additional errors that have not yet been quantified.			
Ocean sink (SOCEAN; section 2.5)			
sparsity in surface fCO <sub>2</sub>	mean, decadal variability and	global, in particular	(Gloege et al., 2021; Denvil-Sommer et al., 2021; Hauck et al., 2023)

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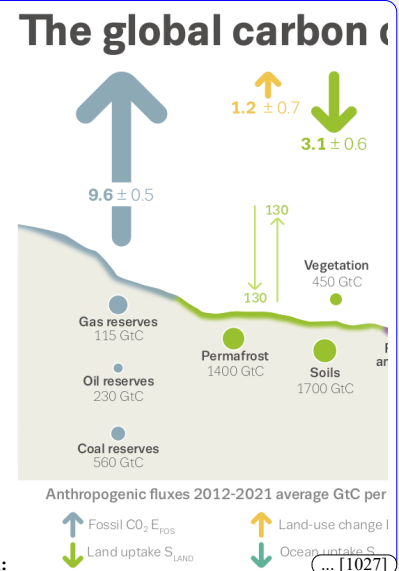
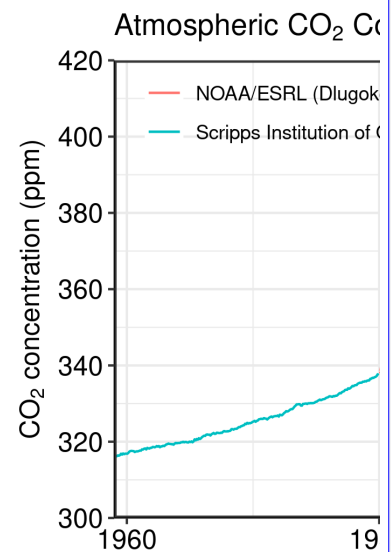
observations	trend	southern hemisphere		
riverine carbon outgassing and its anthropogenic perturbation	annual to decadal	global, in particular partitioning between Tropics and South		(Aumont et al., 2001; Lacroix et al., 2020; Cris et al., 2022)
Models underestimate interior ocean anthropogenic carbon storage	annual to decadal	global		(Friedlingstein et al., 2021, this study, DeVries et al., 2023, see also Terhaar et al., 2022)
near-surface temperature and salinity gradients	mean on all time-scales	global		(Watson et al., 2020; Dong et al., 2022; Bellenger et al., 2023)
Land sink (SLAND; section 2.6)				
strength of CO <sub>2</sub> fertilisation	multi-decadal trend	global		(Wenzel et al., 2016; Walker et al., 2021)
response to variability in temperature and rainfall	annual to decadal	global; in particular tropics		(Cox et al., 2013; Jung et al., 2017; Humphrey et al., 2018; 2021)
nutrient limitation and supply	annual to decadal	global		(Zaehle et al., 2014)
carbon allocation and tissue turnover rates	annual to decadal	global		(De Kauwe et al., 2014; O'Sullivan et al., 2022)
tree mortality	annual	global in particular tropics		(Hubau et al., 2021; Brien et al., 2020)
response to diffuse radiation	annual	global		(Mercado et al., 2009; O'Sullivan et al., 2021)

**Table 10.** Major known sources of uncertainties in each component of the Global Carbon Budget, defined as input data or processes that have a demonstrated effect of at least  $\pm 0.3 \text{ GtC yr}^{-1}$ .

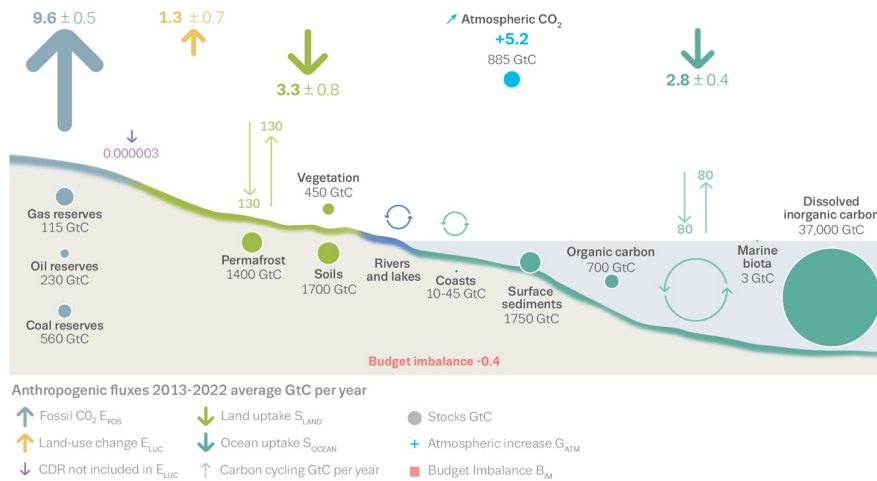
## Figures and Captions



**Figure 1.** Surface average atmospheric CO<sub>2</sub> concentration (ppm). Since 1980, monthly data are from NOAA/GML (Lan et al., 2023) and are based on an average of direct atmospheric CO<sub>2</sub> measurements from multiple stations in the marine boundary layer (Masarie and Tans, 1995). The 1958-1979 monthly data are from the Scripps Institution of Oceanography, based on an average of direct atmospheric CO<sub>2</sub> measurements from the Mauna Loa and South Pole stations (Keeling et al., 1976). To account for the difference of mean CO<sub>2</sub> and seasonality between the NOAA/GML and the Scripps station networks used here, the Scripps surface average (from two stations) was de-seasonalised and adjusted to match the NOAA/GML surface average (from multiple stations) by adding the mean difference of 0.667 ppm, calculated here from overlapping data during 1980-2012.

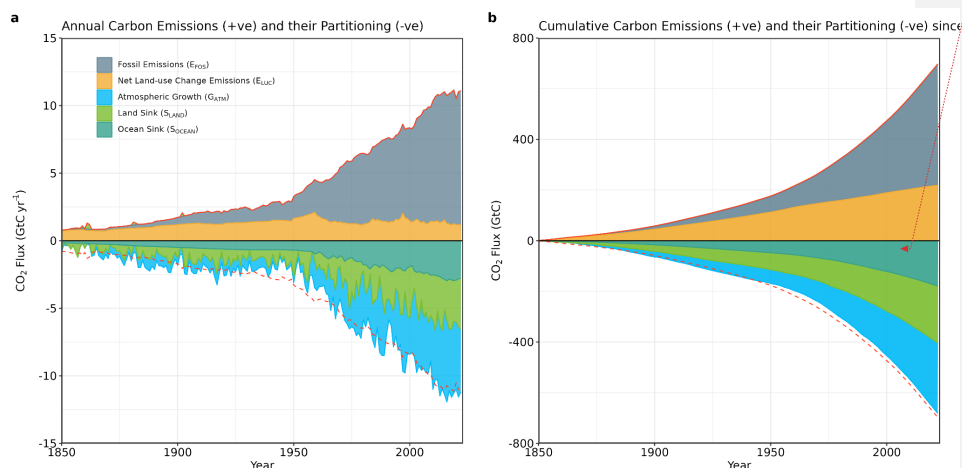


## The global carbon cycle



**Figure 2.** Schematic representation of the overall perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2013-2022. See legends for the corresponding arrows and units. The uncertainty in the atmospheric CO<sub>2</sub> growth rate is very small ( $\pm 0.02$  GtC yr<sup>-1</sup>) and is neglected for the figure. The anthropogenic perturbation occurs on top of an active carbon cycle, with fluxes and stocks represented in the background and taken from Canadell et al. (2021) for all numbers, except for the carbon stocks in coasts which is from a literature review of coastal marine sediments (Price and Warren, 2016).





**Figure 3.** Combined components of the global carbon budget as a function of time, for fossil  $\text{CO}_2$  emissions ( $E_{\text{FOS}}$ , including a small sink from cement carbonation; grey) and emissions from land-use change ( $E_{\text{LUC}}$ ; brown), as well as their partitioning among the atmosphere ( $G_{\text{ATM}}$ ; cyan), ocean ( $S_{\text{OCEAN}}$ ; blue), and land ( $S_{\text{LAND}}$ ; green). Panel (a) shows annual estimates of each flux and panel (b) the cumulative flux (the sum of all prior annual fluxes) since the year 1850. The partitioning is based on nearly independent estimates from observations (for  $G_{\text{ATM}}$ ) and from process model ensembles constrained by data (for  $S_{\text{OCEAN}}$  and  $S_{\text{LAND}}$ ) and does not exactly add up to the sum of the emissions, resulting in a budget imbalance (BIM) which is represented by the difference between the bottom red line (mirroring total emissions) and the sum of carbon fluxes in the ocean, land, and atmosphere reservoirs. All data are in  $\text{GtC yr}^{-1}$  (panel a) and  $\text{GtC}$  (panel b). The  $E_{\text{FOS}}$  estimate is based on a mosaic of different datasets, and has an uncertainty of  $\pm 5\%$  ( $\pm 1\sigma$ ). The  $E_{\text{LUC}}$  estimate is from three bookkeeping models (Table 4) with uncertainty of  $\pm 0.7 \text{ GtC yr}^{-1}$ . The  $G_{\text{ATM}}$  estimates prior to 1959 are from Joos and Spahni (2008) with uncertainties equivalent to about  $\pm 0.1$ – $0.15 \text{ GtC yr}^{-1}$  and from Lan et al. (2023) since 1959 with uncertainties of about  $\pm 0.07 \text{ GtC yr}^{-1}$  during 1959–1979 and  $\pm 0.02 \text{ GtC yr}^{-1}$  since 1980. The  $S_{\text{OCEAN}}$  estimate is the average from Khatiwala et al. (2013) and DeVries (2014) with uncertainty of about  $\pm 30\%$  prior to 1959, and the average of an ensemble of models and an ensemble of  $f\text{CO}_2$  products (Table 4) with uncertainties of about  $\pm 0.4 \text{ GtC yr}^{-1}$  since 1959. The  $S_{\text{LAND}}$  estimate is the average of an ensemble of models (Table 4) with uncertainties of about  $\pm 1 \text{ GtC yr}^{-1}$ . See the text for more details of each component and their uncertainties.

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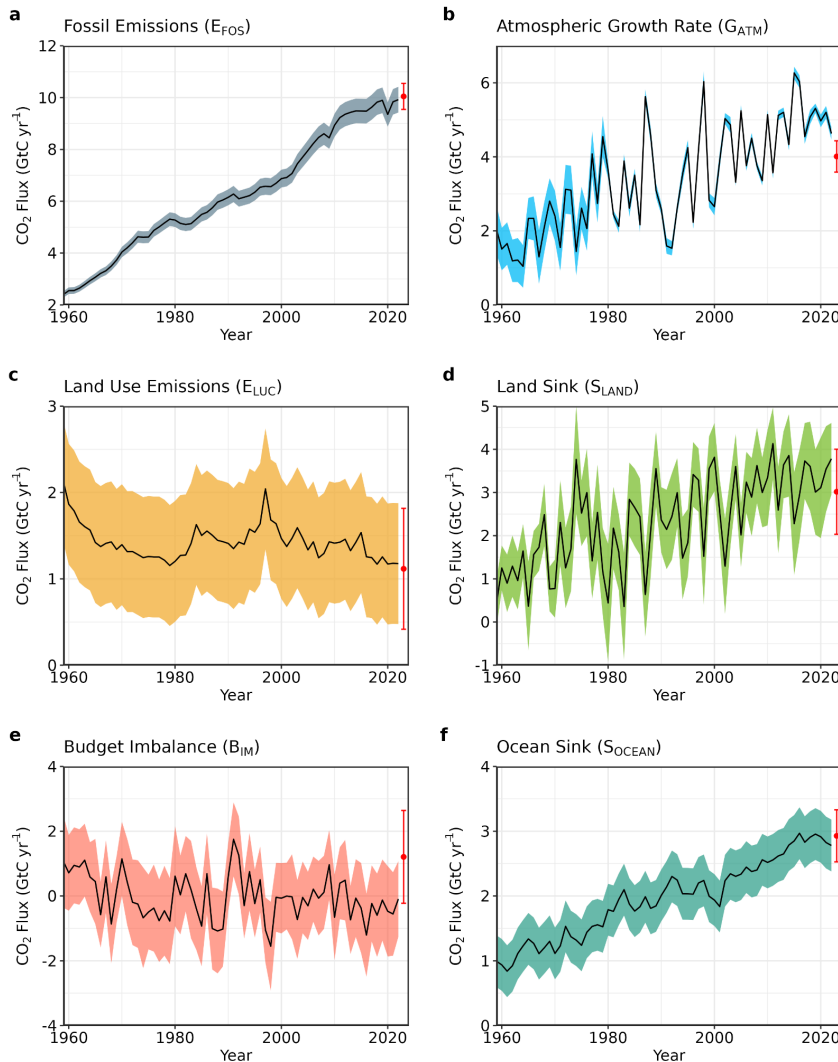
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**Figure 4.** Components of the global carbon budget and their uncertainties as a function of time, presented individually for (a) fossil CO<sub>2</sub> and cement carbonation emissions ( $E_{FOS}$ ), (b) growth rate in atmospheric CO<sub>2</sub> concentration ( $G_{ATM}$ ), (c) emissions from land-use change ( $E_{LUC}$ ), (d) the land CO<sub>2</sub> sink ( $S_{LAND}$ ), (e) the ocean CO<sub>2</sub> sink ( $S_{OCEAN}$ ), (f) the budget imbalance that is not accounted for by the other terms. Positive values of  $S_{LAND}$  and  $S_{OCEAN}$  represent a flux from the atmosphere to land or the ocean. All data are in GtC yr<sup>-1</sup> with the uncertainty bounds representing  $\pm 1$  standard deviation in shaded colour. Data sources are as in Figure 3. The red dots indicate our projections for the year 2023 and the red error bars the uncertainty in the projections (see methods).

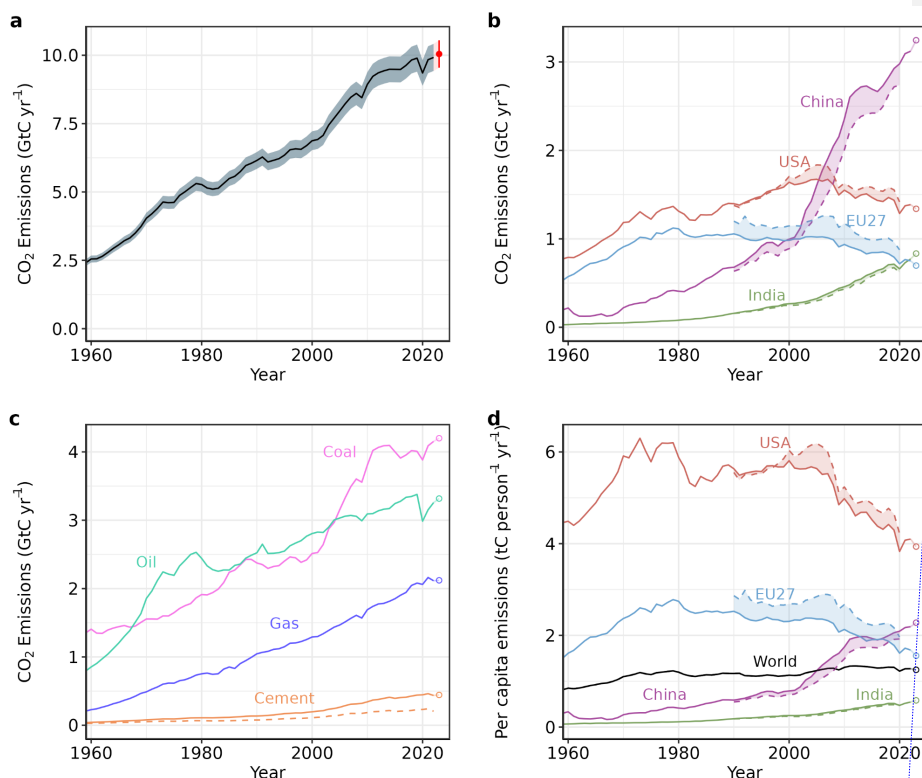
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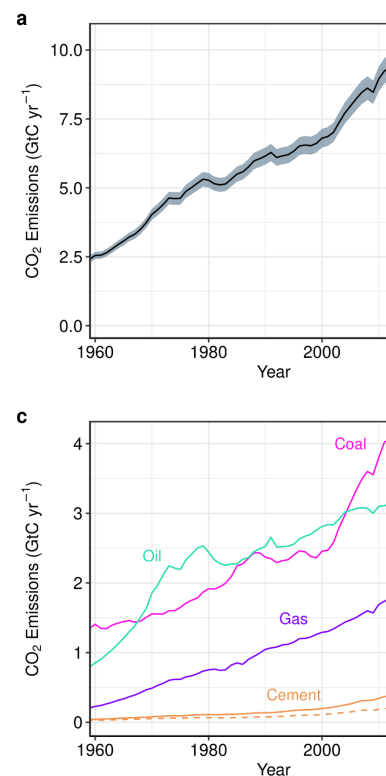
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**Figure 5.** Fossil CO<sub>2</sub> emissions for (a) the globe, including an uncertainty of  $\pm 5\%$  (grey shading) and a projection through the year 2023 (red dot and uncertainty range), (b) territorial (solid lines) and consumption-based (dashed lines) emissions for the top three country emitters (USA, China, India) and for the European Union (EU27), (c) global emissions by fuel type, including coal, oil, gas, and cement, and cement minus cement carbonation (dashed), and (d) per-capita emissions the world and for the large emitters as in panel (b). Territorial emissions are primarily from a draft update of Gilfillan and Marland (2021) except for national data for Annex I countries for 1990–2021, which are reported to the UNFCCC as detailed in the text, as well as some improvements in individual countries, and extrapolated forward to 2022 using data from Energy Institute. Consumption-based emissions are updated from Peters et al. (2011a). See Section 2.1 and Appendix C.1 for details of the calculations and data sources.



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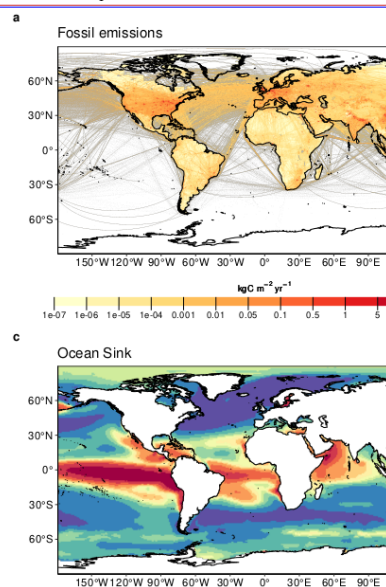
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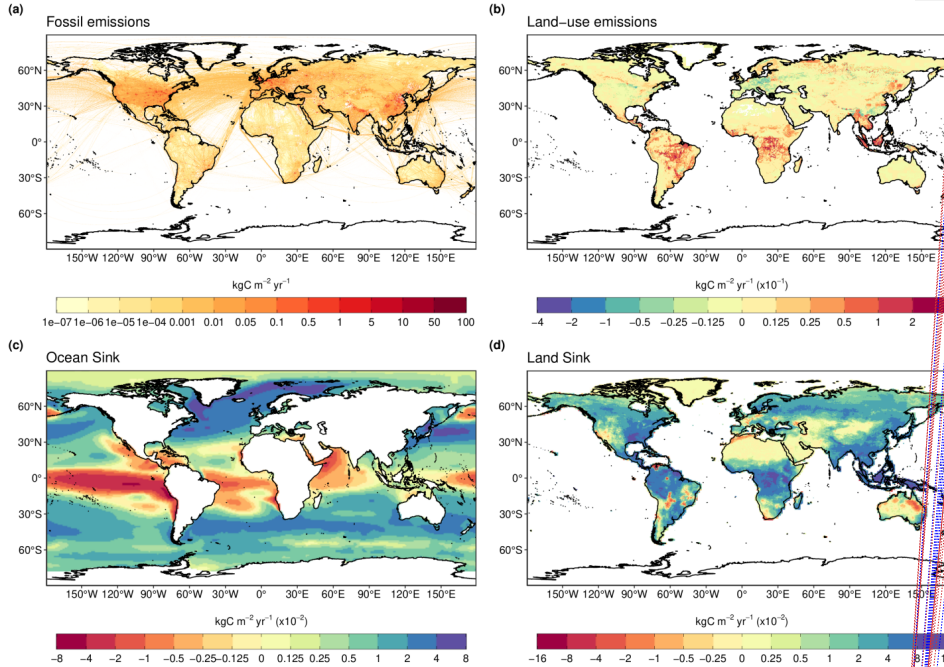
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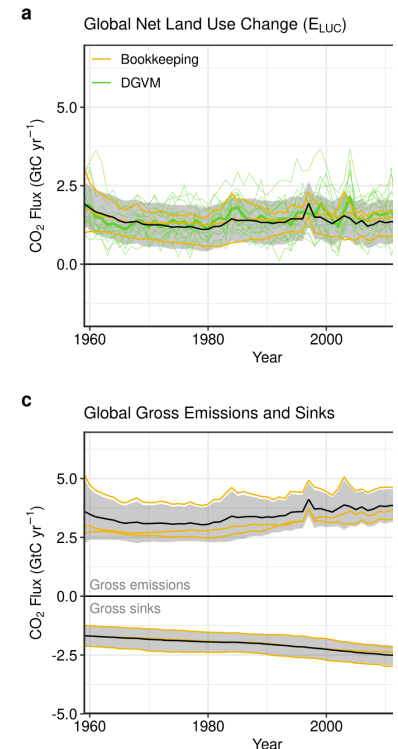
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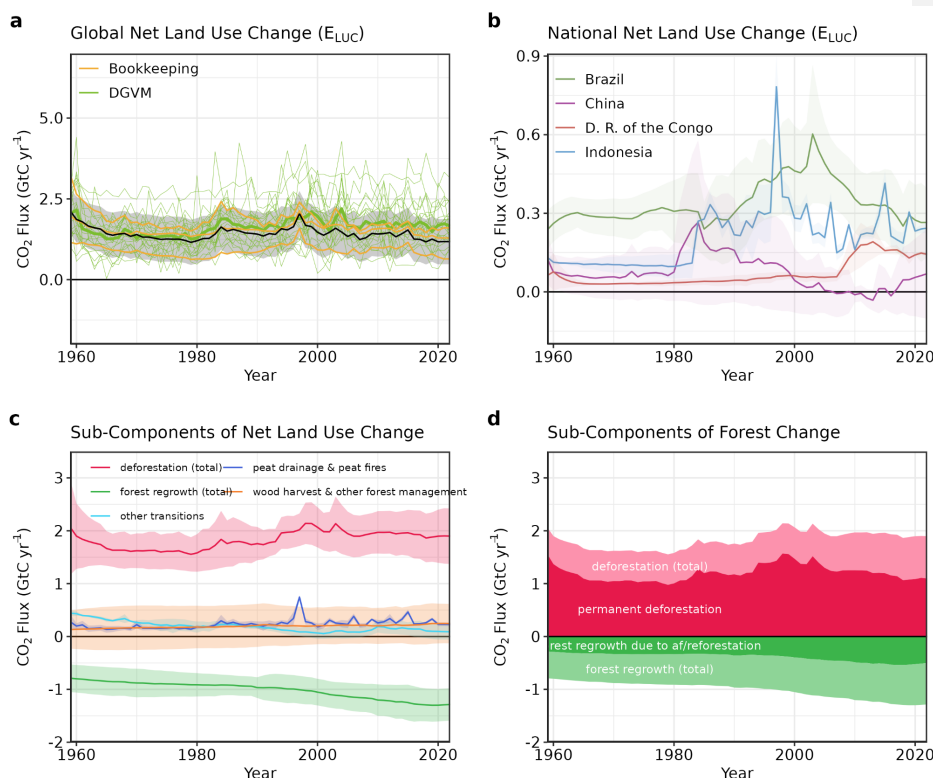
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**Figure 6.** The 2013–2022 decadal mean components of the global carbon budget, presented for (a) fossil CO<sub>2</sub> emissions ( $E_{FOS}$ ), (b) land-use change emissions ( $E_{LUC}$ ), (c) the ocean CO<sub>2</sub> sink ( $S_{OCEAN}$ ), and (d) the land CO<sub>2</sub> sink ( $S_{LAND}$ ). Positive values for  $E_{FOS}$  and  $E_{LUC}$  represent a flux to the atmosphere, whereas positive values of  $S_{OCEAN}$  and  $S_{LAND}$  represent a flux from the atmosphere to the ocean or the land (carbon sink). In all panels, yellow/red colours represent a source (flux from the land/ocean to the atmosphere), green/blue colours represent a sink (flux from the atmosphere into the land/ocean). All units are in  $\text{kgC m}^{-2} \text{yr}^{-1}$ . Note the different scales in each panel.  $E_{FOS}$  data shown is from GCP-GridFEDv2023.1. The  $E_{LUC}$  map shows the average  $E_{LUC}$  from the three bookkeeping models plus emissions from peat drainage and peat fires. Gridded  $E_{LUC}$  estimates for H&C2023 and OSCAR are derived by spatially distributing their national data based on the spatial patterns of BLUE gross fluxes in each country (see Schwingshackl et al., 2022, for more details about the methodology).  $S_{OCEAN}$  data shown is the average of GOBMs and data-products means, using GOBMs simulation A, no adjustment for bias and drift applied to the gridded fields (see Section 2.5).  $S_{LAND}$  data shown is the average of the DGVMs for simulation S2 (see Section 2.6).





**Figure 7.** Net CO<sub>2</sub> exchanges between the atmosphere and the terrestrial biosphere related to land use change.

(a) Net CO<sub>2</sub> emissions from land-use change ( $E_{LUC}$ ) with estimates from the three bookkeeping models (yellow lines) and the budget estimate (black with  $\pm 1\sigma$  uncertainty), which is the average of the three bookkeeping models. Estimates from individual DGVMs (narrow green lines) and the DGVM ensemble mean (thick green line) are also shown. (b) Net CO<sub>2</sub> emissions from land-use change from the four countries with largest cumulative emissions since 1959. Values shown are the average of the three bookkeeping models, with shaded regions as  $\pm 1\sigma$  uncertainty. (c) Sub-components of  $E_{LUC}$ : (i) emissions from deforestation (including permanent deforestation and deforestation in shifting cultivation cycles), (ii) emissions from peat drainage & peat fires, (iii) removals from forest (re-)growth (including forest (re-)growth due to afforestation and reforestation and forest regrowth in shifting cultivation cycles), (iv) fluxes from wood harvest and other forest management (comprising slash and product decay following wood harvest, regrowth after wood harvest, and fire suppression), and (v) emissions and removals related to other land-use transitions. The sum of the five components is  $E_{LUC}$  shown in panel (a). (d) Sub-components of 'deforestation (total)' and of 'forest (re-)growth (total)': (i) deforestation in shifting cultivation cycles, (ii) permanent deforestation, (iii) forest (re-)growth due to afforestation and/or reforestation, and (iv) forest regrowth in shifting cultivation cycles.

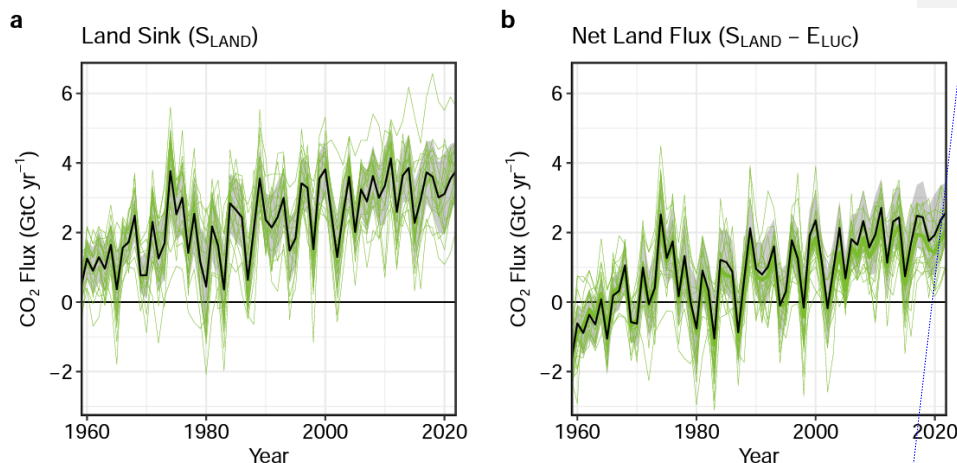
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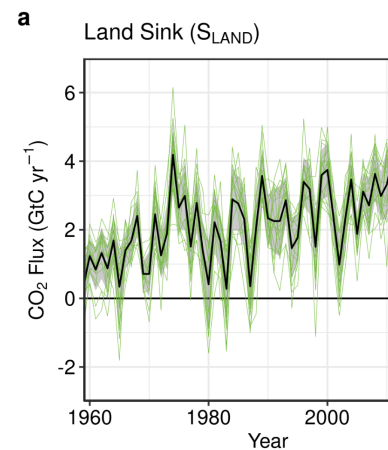
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**Figure 8:** (a) The land CO<sub>2</sub> sink ( $S_{\text{LAND}}$ ) estimated by individual DGVMs (green), as well as the budget estimate (black with  $\pm 1\sigma$  uncertainty), which is the average of all DGVMs. (b) **Net** atmosphere-land CO<sub>2</sub> fluxes ( $S_{\text{LAND}} - E_{\text{LUC}}$ ). The budget estimate of the **net** land flux (black with  $\pm 1\sigma$  uncertainty) combines the DGVM estimate of  $S_{\text{LAND}}$  from panel (a) with the bookkeeping estimate of  $E_{\text{LUC}}$  from Figure 7a. Uncertainties are similarly propagated in quadrature. DGVMs also provide estimates of  $E_{\text{LUC}}$  (see Figure 7a), which can be combined with their own estimates of the land sink. Hence panel (b) also includes an estimate for the **net** land flux for individual DGVMs (thin green lines) and their multi-model mean (thick green line).



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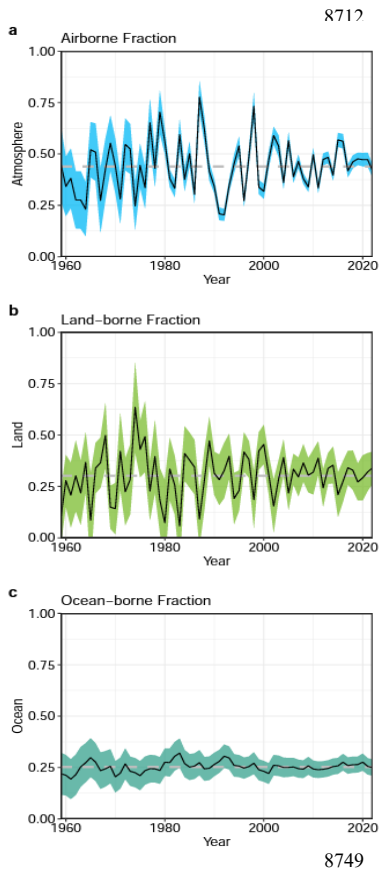
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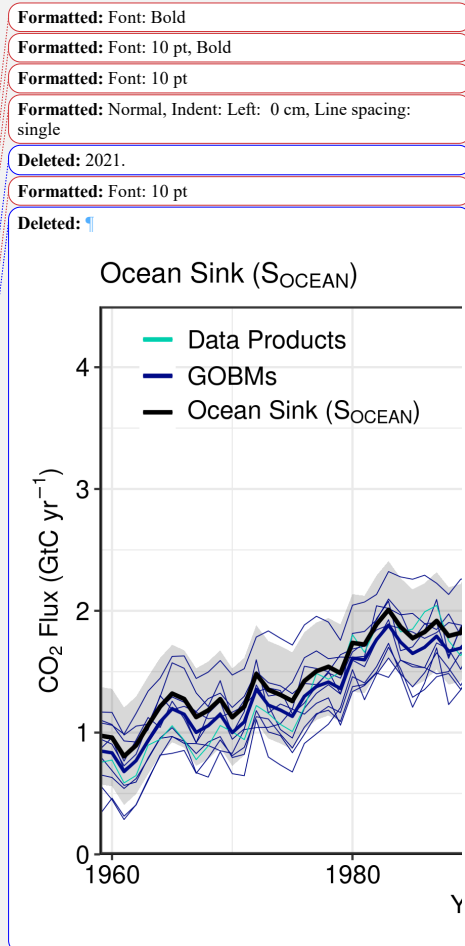
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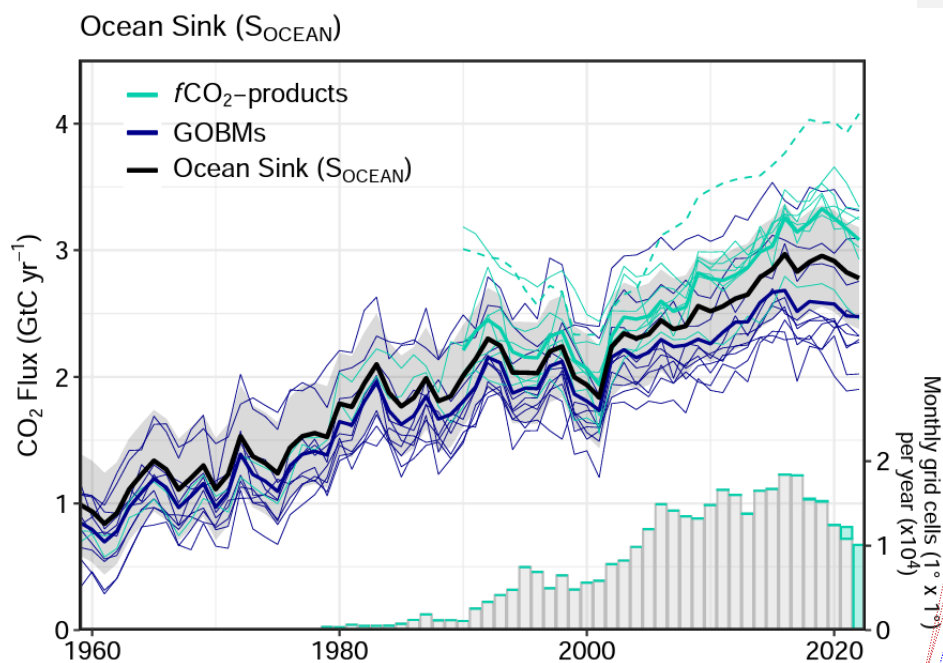
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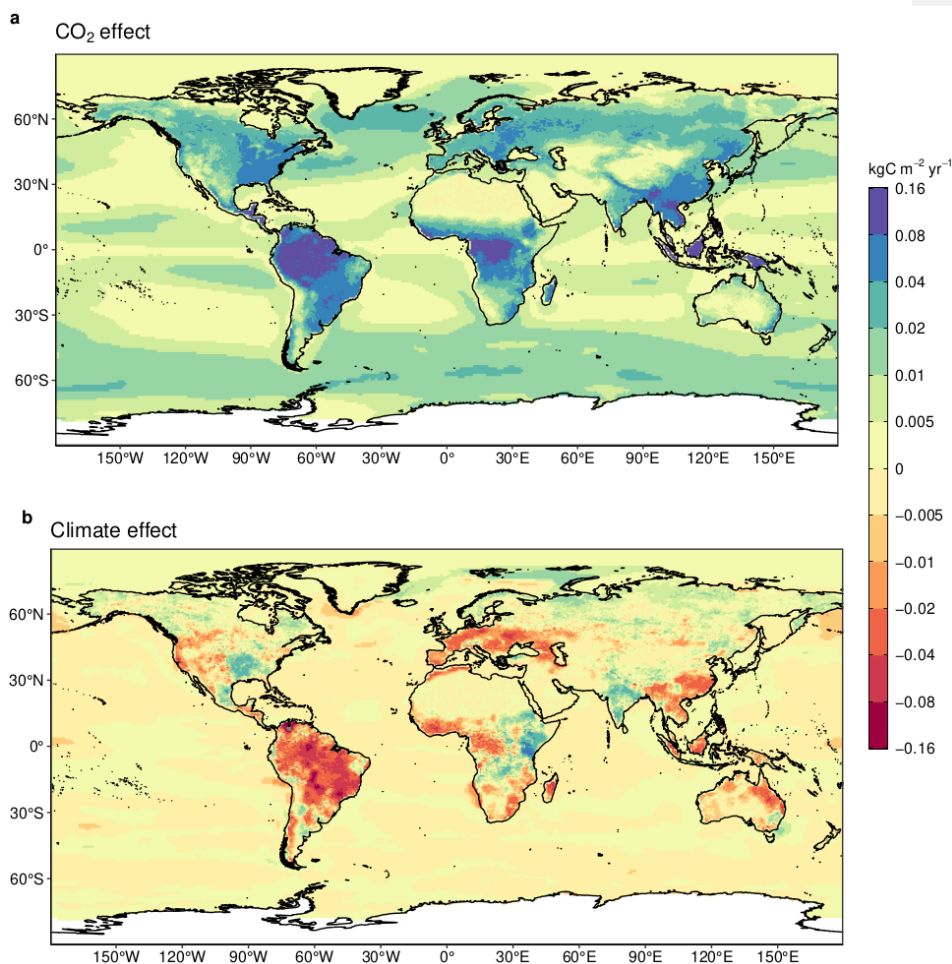


**Figure 9.** The partitioning of total anthropogenic CO<sub>2</sub> emissions ( $E_{FOS} + E_{LUC}$ ) across (a) the atmosphere (airborne fraction), (b) land (land-borne fraction), and (c) ocean (ocean-borne fraction). Black lines represent the central estimate, and the coloured shading represents the uncertainty. The grey dashed lines represent the long-term average of the airborne (44%), land-borne (30%) and ocean-borne (25%) fractions during 1960–2022 (with a BIM of 1%).





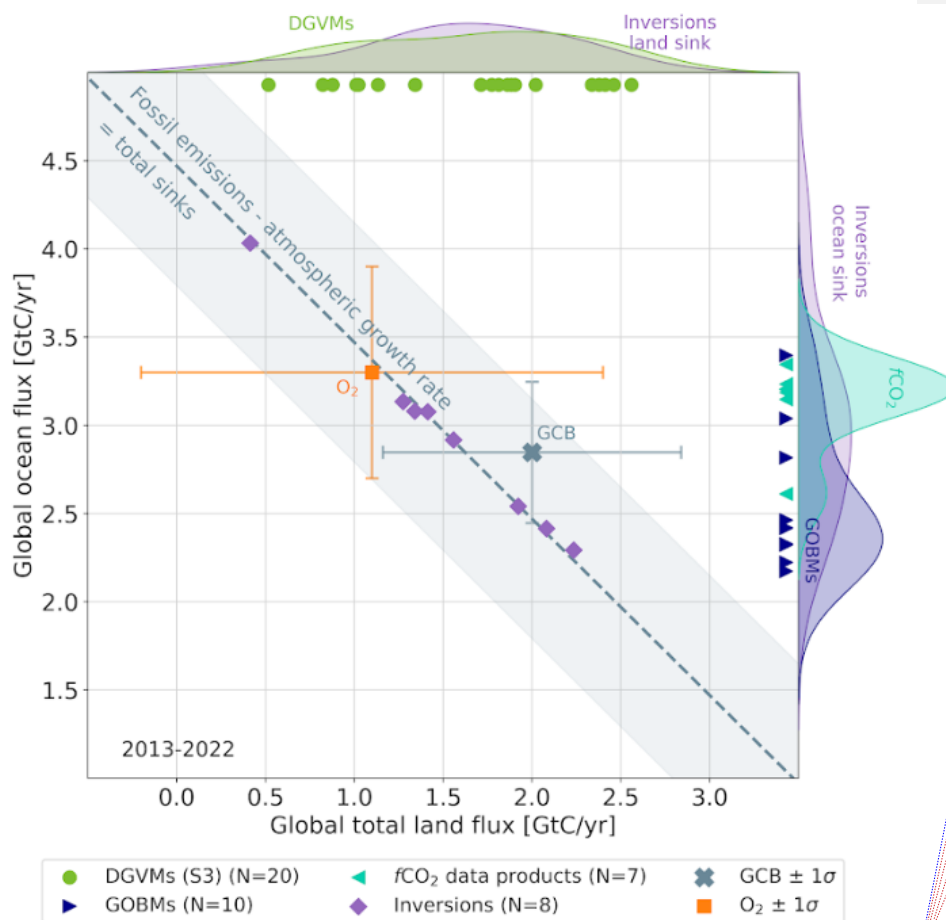
**Figure 10.** Comparison of the anthropogenic atmosphere-ocean  $\text{CO}_2$  flux showing the budget values of  $\text{SO}_{\text{OCEAN}}$  (black; with the uncertainty in grey shading), individual ocean models (royal blue), and the ocean  $f\text{CO}_2$ -products (cyan; with Watson et al. (2020) in dashed line as not used for ensemble mean). Only one  $f\text{CO}_2$ -product (Jena-MLS) extends back to 1959 (Rödenbeck et al., 2022). The  $f\text{CO}_2$ -products were adjusted for the pre-industrial ocean source of  $\text{CO}_2$  from river input to the ocean, by subtracting a source of  $0.65 \text{ GtC yr}^{-1}$  to make them comparable to  $\text{SO}_{\text{OCEAN}}$  (see Section 2.5). Bar-plot in the lower right illustrates the number of  $f\text{CO}_2$  observations in the SOCAT [v2023](#) database (Bakker et al., [v2023](#)). Grey bars indicate the number of data points in SOCAT [v2022](#), and coloured bars the newly added observations in [v2023](#).



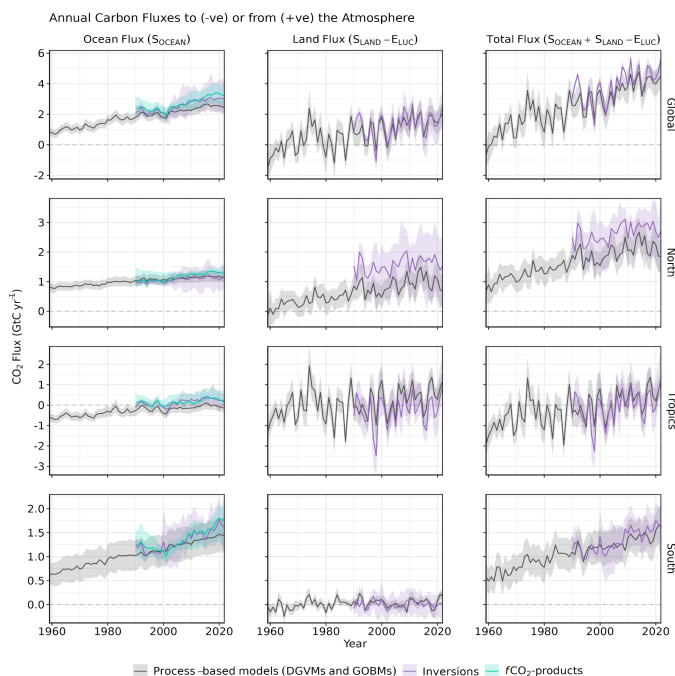
**Figure 11.** Attribution of the atmosphere-ocean ( $S_{\text{OCEAN}}$ ) and atmosphere-land ( $S_{\text{LAND}}$ ) CO<sub>2</sub> fluxes to (a) increasing atmospheric CO<sub>2</sub> concentrations and (b) changes in climate, averaged over the previous decade [2013-2022](#). All data shown is from the processed-based GOBMs and DGVMs. [Note that the](#) sum of ocean CO<sub>2</sub> and climate effects [shown here](#) will not equal the ocean sink shown in Figure 6 which includes the  $f\text{CO}_2$  products. See Appendix C.3.2 and C.4.1 for attribution methodology. Units are in kgC m<sup>-2</sup> yr<sup>-1</sup> (note the non-linear colour scale).

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**Figure 12.** The 2013-2022 decadal mean net atmosphere-ocean and atmosphere-land fluxes derived from the ocean models and  $f\text{CO}_2$  products (y-axis, right and left pointing blue triangles respectively), and from the DGVMs (x-axis, green symbols), and the same fluxes estimated from the inversions (purple symbols). The shaded distributions show the densities of the ensembles of individual estimates. The grey central cross is the mean ( $\pm 1\sigma$ ) of  $S_{\text{OCEAN}}$  and  $(S_{\text{LAND}} - E_{\text{LUC}})$  as assessed in this budget. The grey diagonal line represents the global land + ocean net flux, i.e. global fossil fuel emissions minus the atmospheric growth rate from this budget ( $E_{\text{FOS}} - G_{\text{ATM}}$ ). The orange square represents the ocean and land sink as estimated from the atmospheric  $\text{O}_2$  constraint. Positive values are  $\text{CO}_2$  sinks. Note that the inverse estimates have been scaled for a minor difference between  $E_{\text{FOS}}$  and GridFEDv2023.1 (Jones et al., 2023).



**Figure 13.** CO<sub>2</sub> fluxes between the atmosphere and the Earth's surface separated between land and oceans, globally and in three latitude bands. The ocean flux is  $S_{\text{OCEAN}}$  and the land flux is the net atmosphere-land fluxes from the DGVMs. The latitude bands are (top row) global, (2<sup>nd</sup> row) north (>30°N), (3<sup>rd</sup> row) tropics (30°S-30°N), and (bottom row) south (<30°S), and over ocean (left column), land (middle column), and total (right column). Estimates are shown for: process-based models (DGVMs for land, GOBMs for oceans); inversion systems (land and ocean); and  $f\text{CO}_2$ -products (ocean only). Positive values are CO<sub>2</sub> sinks. Mean estimates from the combination of the process models for the land and oceans are shown (black line) with  $\pm 1$  standard deviation ( $1\sigma$ ) of the model ensemble (grey shading). For the total uncertainty in the process-based estimate of the total sink, uncertainties are summed in quadrature. Mean estimates from the atmospheric inversions are shown (purple lines) with their full spread (purple shading). Mean estimates from the  $f\text{CO}_2$ -products are shown for the ocean domain (light blue lines) with full model spread (light blue shading). The global  $S_{\text{OCEAN}}$  (upper left) and the sum of  $S_{\text{OCEAN}}$  in all three regions represents the anthropogenic atmosphere-to-ocean flux based on the assumption that the preindustrial ocean sink was 0 GtC yr<sup>-1</sup> when riverine fluxes are not considered. This assumption does not hold at the regional level, where preindustrial fluxes can be significantly different from zero. Hence, the regional panels for  $S_{\text{OCEAN}}$  represent a combination of natural and anthropogenic fluxes. Bias-correction and area-weighting were only applied to global  $S_{\text{OCEAN}}$ ; hence the sum of the regions is slightly different from the global estimate (<0.05 GtC yr<sup>-1</sup>).

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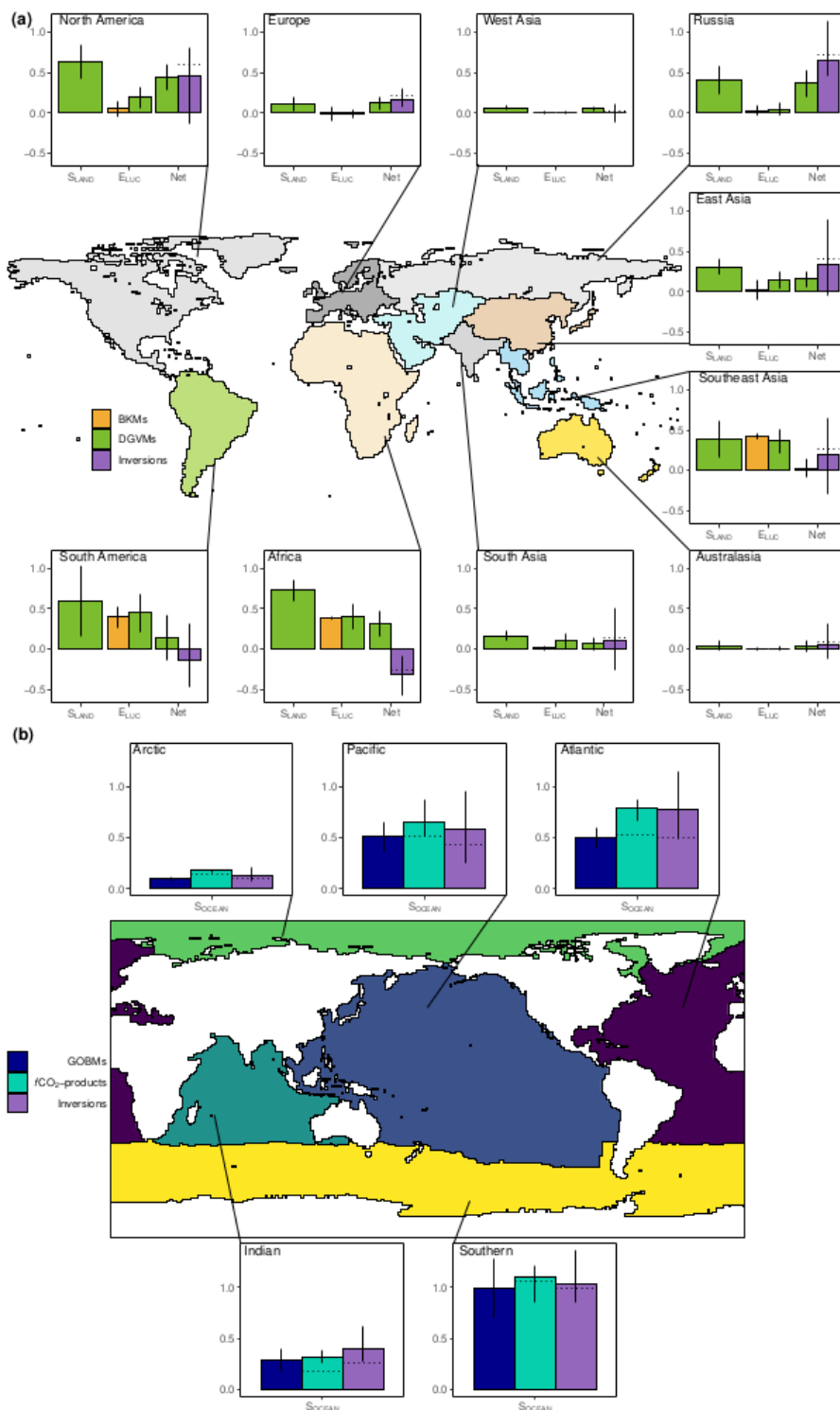
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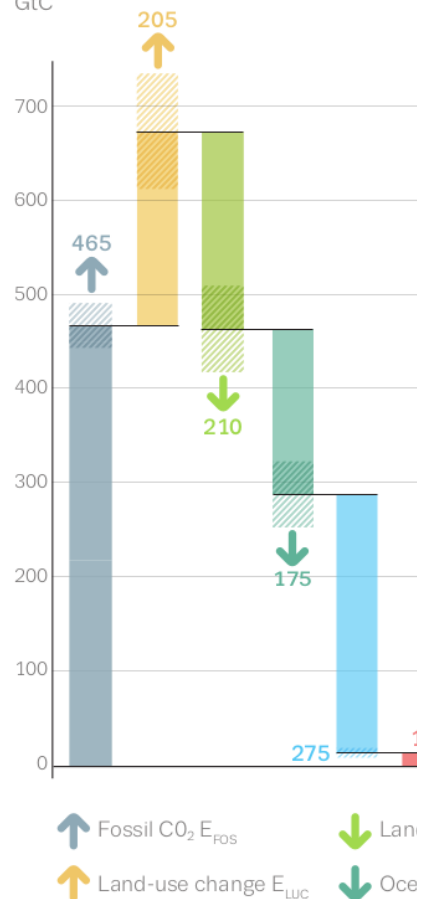
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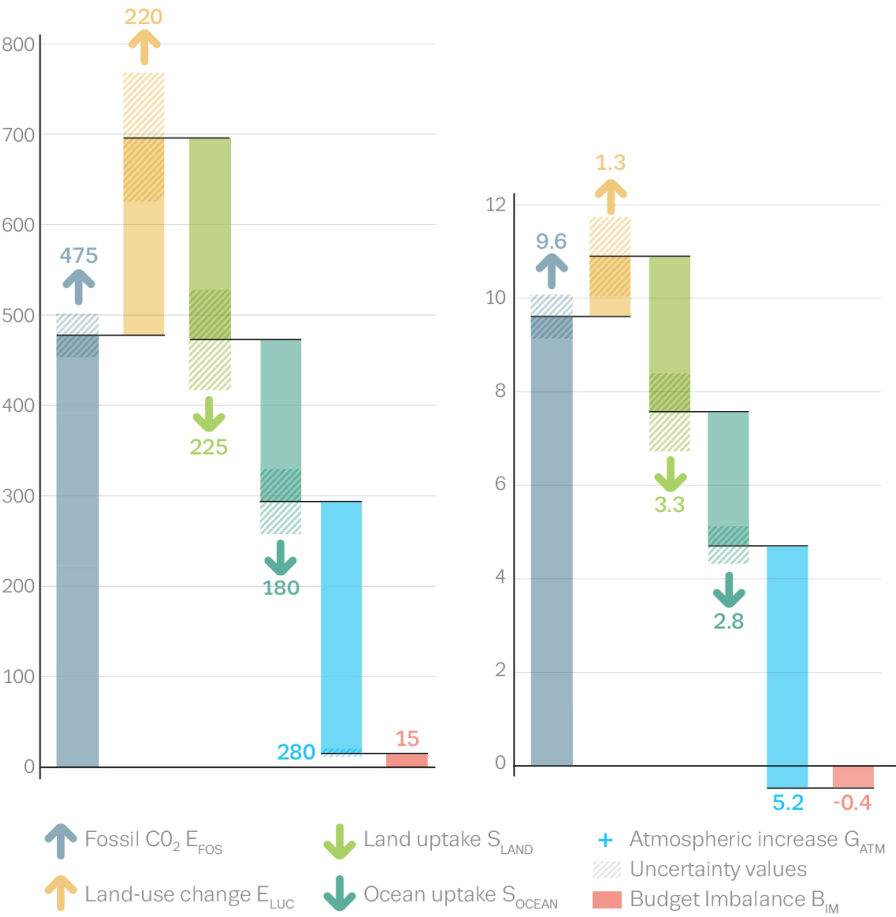
**Figure 14.** Decadal mean (a) land and (b) ocean fluxes for RECCAP-2 regions over 2013-2022. For land fluxes,  $S_{\text{LAND}}$  is estimated by the DGVMs (green bars), with the error bar as  $\pm 1\sigma$  spread among models. A positive  $S_{\text{LAND}}$  is a net transfer of carbon from the atmosphere to the land.  $E_{\text{LUC}}$  fluxes are shown for both DGVMs (green) and bookkeeping models (orange), again with the uncertainty calculated as the  $\pm 1\sigma$  spread. Note, a positive  $E_{\text{LUC}}$  flux indicates a loss of carbon from the land. The net land flux is shown for both DGVMs (green) and atmospheric inversions (purple), including the full model spread for inversions. The net ocean sink ( $S_{\text{OCEAN}}$ ) is estimated by GOBMs (royal blue),  $f\text{CO}_2$ -products (cyan), and atmospheric inversions (purple). Uncertainty is estimated as the  $\pm 1\sigma$  spread for GOBMs, and the full model spread for the other two products. The dotted lines show the  $f\text{CO}_2$ -products and inversion results without river flux adjustment. Positive values are  $\text{CO}_2$  sinks.

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# Anthropogenic carbon flows

Cumulative changes 1850-2022 GtC

Mean fluxes 2013-2022 GtC per year



**Figure 15.** Cumulative changes over the 1850-2022 period (left) and average fluxes over the 2013-2022 period (right) for the anthropogenic perturbation of the global carbon cycle. See the caption of Figure 3 for key information and the methods in text for full details.

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**Figure 16.** Kaya decomposition of the main drivers of fossil CO<sub>2</sub> emissions, considering population, GDP per person, Energy per GDP, and CO<sub>2</sub> emissions per energy, for China (top left), USA (top right), EU27 (middle left), India (middle right), Rest of the World (bottom left), and World (bottom right). Black dots are the annual fossil CO<sub>2</sub> emissions growth rate, coloured bars are the contributions from the different drivers. A general trend is that population and GDP growth put upward pressure on emissions, while energy per GDP and, more recently, CO<sub>2</sub> emissions per energy put downward pressure on emissions. Both the COVID-19 induced changes during 2020 and the recovery in 2021 led to a stark contrast to previous years, with different drivers in each region. [The EU27 had strong Energy/GDP improvements in 2022.](#)



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## 5

Change in this study		Bookkeeping Models	PGVMs																			
H & C 2023	BLUE	OSCAR	CA-BL-E-POP	C-L-A-S-I-C	C-L-E-M-S-I-O	D-L-E-M	E-D-v3	EL-M	IBIS	J-S-A-M	J-B-A-C-H	J-S-B-A-C-H	LP-J-G-U-E-S	LP-J-L-E-S	LP-J-W-S-L	LP-X-B-e-n	O-C-N-v2	O-C-H-I-D-E-E-v3	S-D-G-V-M	V-I-S-I-T	Y135	C-A-R-D-A-M-O-M







**Table A2. Comparison of the processes and model set up for the Global Ocean Biogeochemistry Models for their estimates of SOCEAN. See Table 4 for model references.**

	<a href="#">NEMO-PlankTOM12</a>	<a href="#">NEMO-PISCES (IPSL)</a>	<a href="#">MICOM-HAMOC6 (NorESM1-OCv1.2)</a>	<a href="#">MPIOM-HAMOC6</a>	<a href="#">FESOM-2.1-REcoM3</a>	<a href="#">NEMO3.6-PISCESv2-gas (CNRM)</a>	<a href="#">MOM6-COBALT (Princeton)</a>	<a href="#">CESM-ETHZ</a>	<a href="#">MRI-ESM2-2</a>	<a href="#">ACCESS (CSIRO)</a>
<b>Model specifics</b>										
Physical ocean model	NEMOv3.6-ORCA2	NEMOv3.6-eORCA1L7	MICOM (NorESM1-OCv1.2)	MPIOM	FESOM-2.1	NEMOv3.6-GELATOv6-eORCA1L7	MOM6-SIS2	CESMv1.3 (ocean model based on POP2)	MRI-COMv5	ACCESS (CSIRO)
Biogeochemistry model	PlankTOM12	PISCESv2	HAMOC6 (NorESM1-OCv1.2)	HAMOC6	REcoM3	PISCESv2-gas	COBALTv2	BEC (modified & extended)	NPZD	WOMBAT
Horizontal resolution	2° lon, 0.3 to 1.5° lat	1° lon, 0.3 to 1° lat	1° lon, 0.17 to 0.25 lat	1.5°	unstructured mesh, 20-120 km resolution (CORE mesh)	1° lon, 0.3 to 1° lat	0.5° lon, 0.25 to 0.5° lat	1.125° lon, 0.53° to 0.27° lat	1° lon, 0.3 to 0.5° lat	1° lon, 0.3 to 0.5° lat
Vertical resolution	31 levels	75 levels, 1m at the surface	51 isopycnal layers + 2 layers representing a bulk mixed layer	40 levels	46 levels, 10 m spacing in the top 100 m	75 levels, 1m at surface	75 levels hybrid coordinates, 2m at surface	60 levels with 1-level bottom boundary layer	50 levels, 20 m at top 100 m	50 levels, 20 m at top 100 m
Total ocean area on native grid (km <sup>2</sup> )	3.6080E+08	3.6270E+08	3.6006E+08	3.6598E+08	3.6435E+08	3.6270E+14	3.6111E+08	3.5926E+08	3.6096E+08	3.6245E+08
Gas-exchange parameterization	Wanninkhof et al. (1992)	Orr et al. (2017)	Orr et al. (2017) but with a=0.337	Orr et al. (2017)	Orr et al. (2017)	Orr et al. (2017); Wanninkhof et al. (2014)	Orr et al. (2017)	Wanninkhof (1992), coefficient a scaled down to 0.31	Orr et al. (2017)	Wanninkhof et al. (1992)
CO <sub>2</sub> chemistry routines	OCMIP2 (Orr et al. 2017)	mocsy	Following Dickson et al. (2007)	Following Dickson et al. (2007)	mocsy	mocsy	mocsy	OCMIP2 (Orr et al. 2017)	mocsy	OCMIP2 (Orr et al. 2017)
River input (PgC/yr) (organic/inorganic DIC)	0.723 / -	0.61 / -	0.77 / -	0 / 0	0 / 0	0.611 / -	-0.07 / -0.15	0.33 / -	0 / 0	0 / 0
Net flux to sediment (PgC/yr) (organic/other)	0.723 / -	0.59 / -	around 0.54 / -	- / 0.44	0 / 0	around 0.656 / -	-0.11 / -0.07 (CaCO <sub>3</sub> )	0.21 / -	0 / 0	0 / 0
<b>SPIN-UP procedure</b>										
Initialisation of carbon chemistry	GLODAPv1 (preindustrial DIC)	GLODAPv2 (preindustrial DIC)	GLODAPv1 (preindustrial DIC)	initialization from previous simulation	GLODAPv2 (preindustrial DIC)	GLODAPv2	GLODAPv2 (preindustrial DIC)	GLODAPv2 (preindustrial DIC)	GLODAPv2 (preindustrial DIC)	GLODAPv2 (preindustrial DIC)

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Table A3: Description of ocean [fCO<sub>2</sub>](#) products used for assessment of SOCEAN. See Table 4 for references.

	<a href="#">Jena-MLS</a>	<a href="#">MPI-SOMFFN</a>	<a href="#">CMEMS-LSCE-FFNN</a>	<a href="#">UOEx-Watson</a>	<a href="#">NIES-ML3</a>	<a href="#">JMA-MLR</a>	<a href="#">OS-ETHZ-GRaCER</a>	<a href="#">LDEO HPD</a>
<b>Method</b>	Spatio-temporal interpolation (version <a href="#">oc v2023</a> ). Spatio-temporal field of ocean-internal carbon sources/sinks is fit to the SOCATv2022 pCO <sub>2</sub> data. Includes a multi-linear regression against environmental drivers to bridge data gaps.	A feed-forward neural network (FFN) determines non-linear relationship between SOCAT pCO <sub>2</sub> measurements and environmental predictor data for 16 biogeochemical provinces (defined through a self-organizing map, SOM) and is used to fill the existing data gaps.	An ensemble of neural network models trained on 100 subsampled datasets from SOCAT and environmental predictors. The models are used to reconstruct sea surface fugacity of CO <sub>2</sub> and convert to air-sea CO <sub>2</sub> fluxes.	Modified MPI-SOMFFN with <a href="#">SOCATv2023 fCO<sub>2</sub></a> database, <a href="#">corrected</a> to the subskin temperature ( <a href="#">ESA CCI v2.1</a> ) of the ocean as measured by <a href="#">satellites</a> (Goddijn-Murphy et al. 2015). Flux calculation corrected for the cool and salty surface skin. Monthly skin temperature <a href="#">calculated</a> from <a href="#">ESA CCI v2.1</a> (Merchant et al. 2019) <a href="#">with the cool skin difference</a> <a href="#">calculated using NOAA COARE 3.5</a> .	<a href="#">The ensemble of a random forest, a gradient boost machine, and a feed forward neural network</a> trained on <a href="#">SOCAT 2023</a> . fCO <sub>2</sub> and environmental predictor data. <a href="#">The interannual trend of fCO<sub>2</sub> was estimated first by the decadal trend of atmospheric CO<sub>2</sub> and then corrected by a so-called leave-one-year-out validation method. The trend was used to normalize fCO<sub>2</sub> to the reference year 2005 for model training and fCO<sub>2</sub> prediction. The monthly fCO<sub>2</sub> maps were reconstructed using the prediction and trend.</a>	Fields of total alkalinity (TA) were estimated by using a multiple linear regressions (MLR) method based on <a href="#">GLODAPv2.202</a> and satellite observation data. <a href="#">SOCATv2023</a> fCO <sub>2</sub> data were converted to dissolved inorganic carbon (DIC) with the TA. Fields of DIC were estimated by using a MLR method based on the DIC and satellite observation data.	Geospatial Random Cluster Ensemble Regression is a two-step cluster-regression approach, where multiple clustering instances with slight variations are run to create an ensemble of estimates. We use K-means clustering and a combination of Gradient boosted trees and Feed-forward neural networks to estimate SOCAT <a href="#">v2023 fCO<sub>2</sub></a> .	Based on fCO <sub>2</sub> -misfit between observed fCO <sub>2</sub> and eight <a href="#">Global Carbon Budget</a> ocean biogeochemical models. The extreme Gradient Boosting method links this misfit to environmental observations to reconstruct the model misfit across all space and time, which is then added back to model-based fCO <sub>2</sub> estimate. The final reconstruction of surface fCO <sub>2</sub> is the average across the eight reconstruction s. <a href="#">A climatology of the misfit is calculated for the years 2000-2022 is used as an offset for years prior to 1982 when no/limited environmental observations are available to train the ML algorithm.</a>
<b>Gas-exchange parameterization</b>	<a href="#">Wanninkhof (1992)</a> . Transfer coefficient k scaled to match a global mean transfer rate of 16.5 cm/hr by (Naegler, 2009).	<a href="#">Wanninkhof (1992)</a> . Transfer coefficient k scaled to match a global mean transfer rate of 16.5 cm/hr.	<a href="#">Wanninkhof 2014</a> . Transfer coefficient k scaled to match a global mean transfer rate of 16.5 cm/hr (Naegler, 2009).	<a href="#">Nightingale et al. (2000)</a>	<a href="#">Wanninkhof (2014)</a> . Transfer coefficient k scaled to match a global mean transfer rate of 16.5 cm/hr (Naegler, 2009).	<a href="#">Wanninkhof (2014)</a> . Transfer coefficient k scaled to match a global mean transfer rate of 16.5 cm/hr (Naegler, 2009).	<a href="#">Wanninkhof (1992)</a> . averaged and scaled to match a global mean transfer rate of 16.5 cm/hr (after Naegler 2009; Fay & Gregor et al. 2021).	<a href="#">Transfer coefficient k scaled to match a global mean transfer rate of 16.5 cm/hr</a> (Naegler 2009).

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**Table A4.** Comparison of the inversion set up and input fields for the atmospheric inversions. Atmospheric inversions see the full CO<sub>2</sub> fluxes, including the anthropogenic and pre-industrial fluxes. Hence they need to be adjusted for the pre-industrial flux of CO<sub>2</sub> from the land to the ocean that is part of the natural carbon cycle before they can be compared with SOCEAN and SLAND from process models. See Table 4 for references.

Jen a Car boS cop e	Copernicus Atmosphere Monitoring Service (CAMS)	Carbon - Tracker Europe (CTE)	NIS N- CO 2	CT-NOAA	CM S- Flu x	Co per nic us At mo sph ere Mo nit ori ng Ser vic e (CA MS)	GO U LA	TH CO	GC AS v2	Uo E	JAP CA A T
nbe tEX Toc v2 023	v22r1	v20 23	v20 23	CT2022 + CT- NRT.v2023-3	v2023	FT2 3r1	v20 23	v20 23	v20 23	v20 23	v20 23
Version number											
Flags											
Observations											
Atmospheric observations	Flas ks and hou rly fro m vari ous inst itut ion s (ou tlie rs re mo	Hourly resolution (well-mixed conditions) obspace GLOBALVIE Wplus v8.0 (NOAA and ICOS) and NRT v8.1	Hourly reso luti on (wel l-mix ed con diti ons) obs pac k GLO BAL VIE	Hourly resolution (well-mixed conditions) obspace GLOBALVIEWplus v8.0 and NRT v8.1	ACOS- GOSAT v9r, V11.1 OCO-2 scaled standard and obspace GLOBALVIEWplus v8.0 and NRT v8.1	OC O-2 AC OS ret rie val s fro m NA SA v11 .1	OC O-2 AC OS ret rie val s fro m NA SA v11 .1	OC O-2 AC OS ret rie val s fro m NA SA v11 .1	Ho url y v11 y res OC O-2 olu t io XC O2 n we re rie ll- mix val s ed con diti ons to MO 9 nd sta ard	Ho url y v11 y res OC O-2 olu t io XC O2 n we re rie ll- mix val s ed con diti ons to MO 9 nd sta ard	Ho url y v11 y res OC O-2 olu t io XC O2 n we re rie ll- mix val s ed con diti ons to MO 9 nd sta ard









	<a href="#">(-0.3 to +1.4)</a>		<a href="#">(+0.7 to +4.4)</a>		<a href="#">(-4.7 to -0.1)</a>		<a href="#">(-5.1% to +1.8%)</a>		<a href="#">(-0.7 to +3.7)</a>		<a href="#">(-0.8 to +1.8)</a>	
<a href="#">2020 (f)</a>	<a href="#">-6.7%</a>	<a href="#">-5.4%</a>	<a href="#">-1.7%</a>	<a href="#">1.4%</a>	<a href="#">-12.2%</a>	<a href="#">-10.6%</a>	<a href="#">-11.3% (EU27)</a>	<a href="#">-10.9%</a>	<a href="#">-9.1%</a>	<a href="#">-7.3%</a>	<a href="#">-7.4%</a>	<a href="#">-7.0%</a>
<a href="#">2021 (g)</a>	<a href="#">4.8%</a>	<a href="#">5.1%</a>	<a href="#">4.3%</a>	<a href="#">3.5%</a>	<a href="#">6.8%</a>	<a href="#">6.2%</a>	<a href="#">6.3%</a>	<a href="#">6.8%</a>	<a href="#">11.2%</a>	<a href="#">11.1%</a>	<a href="#">3.2%</a>	<a href="#">4.5%</a>
	<a href="#">(4.2% to 5.4%)</a>		<a href="#">(3.0% to 5.4%)</a>		<a href="#">(6.6% to 7.0%)</a>		<a href="#">(4.3% to 8.3%)</a>		<a href="#">(10.7% to 11.7%)</a>		<a href="#">(2.0% to 4.3%)</a>	
<a href="#">2022 (h)</a>	<a href="#">1.1%</a>	<a href="#">0.9%</a>	<a href="#">-1.5%</a>	<a href="#">0.9%</a>	<a href="#">1.6%</a>	<a href="#">1.0%</a>	<a href="#">-1.0%</a>	<a href="#">-1.9%</a>	<a href="#">5.6%</a>	<a href="#">5.8%</a>	<a href="#">2.5%</a>	<a href="#">0.6%</a>
	<a href="#">(0% to 1.7%)</a>		<a href="#">(-3.0% to 0.1%)</a>		<a href="#">(-0.9% to 4.1%)</a>		<a href="#">(-2.9% to 1.0%)</a>		<a href="#">(3.5% to 7.7%)</a>		<a href="#">(0.1% to 2.3%)</a>	
<a href="#">2023 (i)</a>	<a href="#">1.2%</a>		<a href="#">4.0%</a>		<a href="#">-3.4%</a>		<a href="#">-7.1%</a>		<a href="#">8.0%</a>		<a href="#">0.9%</a>	
	<a href="#">(0.2% to 2.3%)</a>		<a href="#">(1.9% to 6.2%)</a>		<a href="#">(-5.9% to -0.9%)</a>		<a href="#">(-9.6% to -4.6%)</a>		<a href="#">(5.8% to 10.2%)</a>		<a href="#">(-0.8% to 2.6%)</a>	

[\(a\) Jackson et al. \(2016\) and Le Quéré et al. \(2015a\)](#), [\(b\) Le Quéré et al. \(2016\)](#), [\(c\) Le Quéré et al. \(2018a\)](#), [\(d\) Le Quéré et al. \(2018b\)](#), [\(e\) Friedlingstein et al., \(2019\)](#), [\(f\) Friedlingstein et al., \(2020\)](#), [\(g\) Friedlingstein et al., \(2022a\)](#), [\(h\) Friedlingstein et al., \(2022b\)](#) [\(i\) This study](#)

[\(i\) EU28 until 2019, EU27 from 2020](#)

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**Table A6 Attribution of fCO<sub>2</sub> measurements for the year 2022 included in SOCATv2023 (Bakker et al., 2016, 2023) to inform ocean fCO<sub>2</sub>-based data products.**

Platform Name	Regions	No. of measurements	Principal Investigators	No. of datasets	Platform Type
Atlantic Explorer	North Atlantic, Tropical Atlantic, coastal	45,321	Bates, N. R.	22	Ship
Atlantic Sail	North Atlantic, coastal	25,691	Steinhoff, T.; Körtzinger, A.	7	Ship
Bell M. Shimida	North Pacific, Tropical Pacific, coastal	42,300	Alin, S. R.; Feely, R. A.	12	Ship
Cap San Lorenzo	North Atlantic, tropical Atlantic, coastal	32,145	Lefèvre, N.	6	Ship
Celtic Explorer	North Atlantic, coastal	36,155	Cronin, M.	3	Ship
Colibri	North Atlantic, tropical Atlantic, coastal	19,199	Lefèvre, N.	3	Ship
Equinox	North Atlantic, Tropical Atlantic, coastal	6,021	Wanninkhof, R.; Pierrot, D.	3	Ship
F.G. Walton Smith	Coastal	19,487	Rodriguez, C.; Millero, F. J.; Barbero, L.; Pierrot, D.; Wanninkhof, R.	14	Ship
Finnmaid	Coastal	218,365	Rehder, G.; Bittig, H. C.; Glockzin, M.	14	Ship
GEOMAR surface buoy 1	Tropical Atlantic	7,223	Paulsen M.; Fielder B.; Körtzinger A.	1	Mooring
GEOMAR waveglider 4	Tropical Atlantic	1,228	Paulsen M.; Fielder B.; Körtzinger A.	1	Autonomous Surface Vehicle
G.O. Sars	Arctic, North Atlantic, coastal	105,798	Skjelvan, I.	12	Ship
GAOIA_149W_60N	Coastal	696	Monacci, N.; Sutton, A.J.	1	Mooring
Gordon Gunter	Coastal	11,542	Wanninkhof, R.; Pierrot, D.	2	Ship
Healy	Arctic, North Pacific, coastal	35,557	Sweeney, C.; Newberger, T.; Sutherland, S. C.; Munro, D. R.	7	Ship
Henry B. Bigelow	Coastal	61,347	Wanninkhof, R.; Pierrot, D.	12	Ship
Heron Island	Coastal	1,531	Tilbrook, B.	1	Mooring
Investigator	Southern Ocean	8,505	Tilbrook, B.; Akl, J.; Neill, C.	1	Ship
Kangaroo Island	Southern Ocean	1,533	Tilbrook, B.	1	Mooring
KC_BUOY	Coastal	7,750	Evans, W.	1	Mooring
Keifu Maru II	North Pacific, Tropical Pacific, coastal	7,264	Enyo, K.	5	Ship
Laurence M. Gould	Southern Ocean	10,640	Sweeney, C.; Newberger, T.; Sutherland, S. C.; Munro, D. R.	5	Ship
Maria Island	Southern Ocean	1,707	Tilbrook, B.	1	Mooring
Marion Dufresne	Indian, Southern Ocean	3,609	Lo Monaco, C.; Metzl, N.	1	Ship
M2_164W_57N	Coastal	926	Monacci, N.; Sutton, A.J.	2	Mooring
Nathaniel B. Palmer	Southern Ocean	19,754	Sweeney, C.; Newberger, T.; Sutherland, S. C.; Munro, D. R.	1	Ship

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New Century 2	North Pacific, Tropical Pacific, North Atlantic, Tropical Atlantic, Southern Ocean, coastal	278,287	Nakaoka, S.-I.; Takao, S.	11	Ship
Nexans - Art and Fenetres	North Atlantic, coastal	4,732	Tanhua, T.	1	Ship
Quadra Island Field Station	Coastal	83,322	Evans, W.	1	Mooring
Roger Revelle	North Pacific, Tropical Pacific, coastal	37,705	Alin, S. R.; Feely, R. A.	3	Ship
Ronald H. Brown	North Atlantic, Tropical Atlantic, coastal	47,311	Wanninkhof, R.; Pierrot, D.	5	Ship
Ryofu Maru III	North Pacific, Tropical Pacific, coastal	8,409	Enyo, K.	7	Ship
Saildrone 1079 EuroSea 2021	Tropical Atlantic, coastal	164	Wimart-Rousseau, C.; Sutton, A.J.; Fiedler, B.	1	Autonomous Surface Vehicle
Sarmiento de Gamboa	Coastal	2,557	Fontela, M.	1	Ship
Seaspan Royal	Coastal	37,081	Evans, W.	2	Mooring
Sikuliaq	Arctic, North Pacific, coastal	61,475	Sweeney, C.; Newberger, T.; Sutherland, S. C.; Munro, D. R.	14	Ship
Simon Stevin	Coastal	58,087	Gkritzalis, T.; Theetaert, H.; Jampens, M.	11	Ship
SOFS 142E 46S	Southern Ocean	1,040	Sutton, A.J.	1	Mooring
Statsraad Lehmkuhl	North Atlantic, Tropical Atlantic, North Pacific, Tropical Pacific, Indian, Southern Ocean, coastal	82,297	Becker, M.; Olsen, A.	5	Ship
Thomas G. Thompson	North Pacific, Tropical Pacific, coastal	51,535	Alin, S. R.; Feely, R. A.	10	Ship
Trans Future 5	North Pacific, Tropical Pacific, Southern Ocean, coastal	167,811	Nakaoka, S.-I.; Nojiri, Y.	15	Ship
Tukuma Arctica	North Atlantic, coastal	58,635	Becker, M.; Olsen, A.	22	Ship
Wakataka Maru	North Pacific, coastal	14,068	Tadokoro, K.; Ono, T.	8	Ship

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**Table A2.** Aircraft measurement programs archived by Cooperative Global Atmospheric Data Integration Project (CGADIP; Schuldt et al. 2022 and 2023) that contribute to the evaluation of the atmospheric inversions (Figure B4).

Site code	Measurement program name in Obspack	Specific doi	Data providers
AAQ	Airborne Aerosol Observatory, Bondville, Illinois		Sweeney, C.; Dlugokencky, E.J.
ABOVE	Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE)	<a href="https://doi.org/10.3334/ORNLDAAC/1404">https://doi.org/10.3334/ORNLDAAC/1404</a>	Sweeney, C., J.B. Miller, A. Karion, S.J. Dinardo, and C.E. Miller. 2016. CARVE: L2 Atmospheric Gas Concentrations, Airborne Flasks, Alaska, 2012-2015. ORNL DAAC, Oak Ridge, Tennessee, USA.
ACG	Alaska Coast Guard		Sweeney, C.; McKain, K.; Karion, A.; Dlugokencky, E.J.
ACT	Atmospheric Carbon and Transport - America		Sweeney, C.; Dlugokencky, E.J.; Baier, B.; Montzka, S.; Davis, K.
AIRCOREN OAA	NOAA AirCore		Colm Sweeney (NOAA) AND Bianca Baier (NOAA)
ALF	Alta Floresta		Gatti, L.V.; Gloor, E.; Miller, J.B.
AOA	Aircraft Observation of Atmospheric trace gases by JMA		ghg_obs@met.kishou.go.jp
BGI	Bradgate, Iowa		Sweeney, C.; Dlugokencky, E.J.
BNE	Beaver Crossing, Nebraska		Sweeney, C.; Dlugokencky, E.J.
BRZ	Berezorechka, Russia		Sasakawa, N.; Machida, T.
CAR	Briggsdale, Colorado		Sweeney, C.; Dlugokencky, E.J.
CMA	Cape May, New Jersey		Sweeney, C.; Dlugokencky, E.J.
CON	CONTRAIL (Comprehensive Observation Network for TRace gases by AirLiner)	<a href="http://dx.doi.org/10.17595/20180208.001">http://dx.doi.org/10.17595/20180208.001</a>	Machida, T.; Ishijima, K.; Niwa, Y.; Tsuboi, K.; Sasaoka, Y.; Matsueda, H.; Sasakawa, M.
CRV	Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE)		Sweeney, C.; Karion, A.; Miller, J.B.; Miller, C.; Dlugokencky, E.J.
DND	Dahlen, North Dakota		Sweeney, C.; Dlugokencky, E.J.
ESP	Estevan Point, British Columbia		Sweeney, C.; Dlugokencky, E.J.
ETL	East Trout Lake, Saskatchewan		Sweeney, C.; Dlugokencky, E.J.
FWI	Fairchild, Wisconsin		Sweeney, C.; Dlugokencky, E.J.
GSFC	NASA Goddard Space Flight Center Aircraft Campaign		Kawa, S.R.; Abshire, J.B.; Riris, H.
HAA	Molokai Island, Hawaii		Sweeney, C.; Dlugokencky, E.J.
HFM	Harvard University Aircraft Campaign		Wofsy, S.C.
HIL	Homer, Illinois		Sweeney, C.; Dlugokencky, E.J.
HIP	HIPPO (HIAPER Pole-to-Pole Observations)	<a href="https://doi.org/10.3334/CDIAC/HIPPO_010">https://doi.org/10.3334/CDIAC/HIPPO_010</a>	Wofsy, S.C.; Stephens, B.B.; Elkins, J.W.; Hinkley, E.J.; Moore, F.
JAGOS-CARIBIC	In-service Aircraft for a Global Observing System		Obersteiner, F.; Boenisch, H.; Gehrlein, T.; Zander, A.; Schuck, T.
JNX	INFLUX (Indianapolis Flux Experiment)		Sweeney, C.; Dlugokencky, E.J.; Shepson, P.B.; Turnbull, J.
LEF	Park Falls, Wisconsin		Sweeney, C.; Dlugokencky, E.J.
MAN	Manaus, Brazil		Miller, J.B.; Martins, G.A.; de Souza, R.A.F.
MEX	High Altitude Global Climate Observation Center, Mexico		Lan, X.; Dlugokencky, E.
NHA	Offshore Portsmouth, New Hampshire (Isles of Shoals)		Sweeney, C.; Dlugokencky, E.J.

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OIL	Oglesby, Illinois	<a href="https://doi.org/10.5065/D6SB445X">https://doi.org/10.5065/D6SB445X</a>	Sweeney, C.; Dlugokencky, E.J.
ORC	ORCAS (O2/N2 Ratio and CO2 Airborne Southern Ocean Study)	X	Stephens, B.B. Sweeney, C., McKain, K., Kort, E.
PFA	Poker Flat, Alaska		Sweeney, C.; Dlugokencky, E.J.
RBA-B	Rio Branco		Gatti, L.V.; Gloor, E.; Miller, J.B.
RTA	Rarotonga		Sweeney, C.; Dlugokencky, E.J.
SAN	Santarem, Brazil		Sweeney, C.; Dlugokencky, E.J.; Gatti, L.V.; Gloor, E.; Miller, J.B.
SCA	Charleston, South Carolina		Sweeney, C.; Dlugokencky, E.J.
SGP	Southern Great Plains, Oklahoma		Sweeney, C.; Dlugokencky, E.J.; Biraud, S.
TAB	Tabatinga		Gatti, L.V.; Gloor, E.; Miller, J.B.
TGC	Offshore Corpus Christi, Texas		Sweeney, C.; Dlugokencky, E.J.
THD	Trinidad Head, California		Sweeney, C.; Dlugokencky, E.J.
UGD	Kajjansi Airfield, Kampala, Uganda		McKain, K; Sweeney, C
ULB	Ulaanbaatar, Mongolia		Sweeney, C.; Dlugokencky, E.J.
WBI	West Branch, Iowa		Sweeney, C.; Dlugokencky, E.J.

(a) Schuldt et al. (2022)

(b) Schuldt et al. (2023)

(a) Schuldt et al. (2022)

(b) Schuldt et al. (2023)

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**Table A8.** Main methodological changes in the global carbon budget since first publication. Methodological changes introduced in one year are kept for the following years unless noted. Empty cells mean there were no methodological changes introduced that year.

Publication year	Fossil fuel emissions			LUC emissions	Reservoirs			Uncertainty & other changes
	Global	Country (territorial)	Country (consumption)		Atmosphere	Ocean	Land	
2006 (a)		Split in regions						
2007 (b)				ELUC based on FAO-FRA 2005; constant ELUC for 2006	1959-1979 data from Mauna Loa; data after 1980 from global average	Based on one ocean model tuned to reproduced observed 1990s sink		$\pm 1\sigma$ provided for all components
2008 (c)				Constant ELUC for 2007				
2009 (d)		Split between Annex B and non-Annex B	Results from an independent study discussed	Fire-based emission anomalies used for 2006-2008		Based on four ocean models normalised to observations with constant delta	First use of five DGVMs to compare with budget residual	
2010 (e)	Projection for current year based on GDP	Emissions for top emitters		ELUC updated with FAO-FRA 2010				
2011 (f)			Split between Annex B and non-Annex B					
2012 (g)		129 countries from 1959	129 countries and regions from 1990-2010 based on GTAP8.0	ELUC for 1997-2011 includes interannual anomalies from fire-based emissions	All years from global average	Based on 5 ocean models normalised to observations with ratio	Ten DGVMs available for SLAND; First use of four models to compare with ELUC	

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2013 (h)		250 countries	134 countries and regions 1990-2011 based on GTAP8.1, with detailed estimates for years 1997, 2001, 2004, and 2007	ELUC for 2012 estimated from 2001-2010 average		Based on six models compared with two data-products to year 2011	Coordinated DGVM experiments for SLAND and ELUC	Confidence levels; cumulative emissions; budget from 1750		
2014 (i)	Three years of BP data	Three years of BP data	Extended to 2012 with updated GDP data	ELUC for 1997-2013 includes interannual anomalies from fire-based emissions		Based on seven models	Based on ten models	Inclusion of breakdown of the sinks in three latitude bands and comparison with three atmospheric inversions		
2015 (j)	Projection for current year based Jan-Aug data	National emissions from UNFCCC extended to 2014 also provided	Detailed estimates introduced for 2011 based on GTAP9			Based on eight models	Based on ten models with assessment of minimum realism	The decadal uncertainty for the DGVM ensemble mean now uses $\pm 1\sigma$ of the decadal spread across models		
2016 (k)	Two years of BP data	Added three small countries; China's emissions from 1990 from BP data (this release only)		Preliminary ELUC using FRA-2015 shown for comparison; use of five DGVMs		Based on seven models	Based on fourteen models	Discussion of projection for full budget for current year		
2017 (l)	Projection includes India-specific data			Average of two bookkeeping models; use of 12 DGVMs		Based on eight models that match the observed sink for the 1990s; no longer normalised	Based on 15 models that meet observation-based criteria (see Sect. 2.5)	Land multi-model average now used in main carbon budget, with the carbon imbalance presented separately; new table of key uncertainties		

2018	Revision in cement emissions; Projection includes EU-specific data	Aggregation of overseas territories into governing nations for total of 213 countries a	Average of two bookkeeping models; use of 16 DGVMs	Use of four atmospheric inversions	Based on seven models	Based on 16 models; revised atmospheric forcing from CRUNCEP to CRUJRA	Introduction of metrics for evaluation of individual models using observations
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a Raupach et al. (2007)

b Canadell et al. (2007)

c GCP (2008)

d Le Quéré et al. (2009)

e Friedlingstein et al. (2010)

f Peters et al. (2012a)

g Le Quéré et al. (2013), Peters et al. (2013)

h Le Quéré et al. (2014)

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**Table A9: Mapping of global carbon cycle models' land flux definitions to the definition of the LULUCF net flux used in national reporting to UNFCCC. Non-intact lands are used here as proxy for "managed lands" in the country reporting, national Greenhouse Gas Inventories (NGHGI) are gap-filled (see Sec. C.2.3 for details). For comparison, we provide FAOSTAT estimates (note that FAOSTAT refers to 2003-2012 and 2012-2021). Units are GtC yr<sup>-1</sup>.**

			2003-2012	2013-2022
ELUC from bookkeeping estimates (from Tab. 5)				
	Total (from Tab. 5)	from DGVMs	1.41	1.27
	in non-forest lands	from DGVMs	2.86	3.35
	in non-intact forest	from DGVMs	0.53	0.58
	in intact forests	from DGVMs	1.87	2.04
ELUC subtract			0.44	0.48
SLAND on non-intact lands	considering non-intact forests only	from bookkeeping ELUC and DGVMs	-0.46	-0.77
National Greenhouse Gas Inventories (LULUCF)			-0.43	0.66
FAOSTAT (LULUCF)			0.35	0.25

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Table A10 - Evaluation of global ocean biogeochemistry models based on comparison with observation-based interior ocean carbon accumulation (Gruber et al., 2019) and process-based evaluation metrics for Atlantic Meridional Overturning Circulation (AMOC), Southern Ocean sea surface salinity and surface ocean Revelle factor (following the RECCAP2 ocean model evaluation chapter, Terhaar et al., in review) and Southern Ocean stratification index (Bourgeois et al., 2022). See supplementary text C3.3 for details of calculation and observational data sources. Note that AMOC from MOM6-Cobalt (Princeton) is only available between 2018 - 2022, which is the value reported here.											
Global Ocean Biogeochemistry Models											
Metric	Obs	SS (CSIR O)	ACCE (CESM -ETHZ)	FESQ REco M	MOM 6- Cobalt (Princeton)	MPIO M- HAM OCC6	MRI-ESM2-2	NEM O- S (IPSL)	NEM O- Plank TOM1 2	NEM O3.6- Sv2- gas (CNRM)	NorESM -OC1.2
Interior ocean anthropogenic carbon accumulation 1994-2007 in GtC yr <sup>-1</sup> (Gruber et al., 2019)											
Global	33.7 ± 4.0	36.4	26.7	30.9	27.3	25.5	27.6	26.0	26.0	26.2	33.5
North	5.9	6.3	5.5	5.8	5.2	6.9	5.6	5.7	4.1	5.6	6.8
Tropics	17.5	15.1	12.2	13.2	11.6	10.9	12.5	11.1	12.6	12.1	13.7
South	10.4	15.0	9.0	11.9	10.6	7.8	9.5	9.2	9.4	8.5	12.9
Atlantic Meridional Overturning Circulation at 26°N, 2005-2021 in Sv (Moat et al., 2023)											
	16.8 ± 0.6	9.5	14.3	10.0	11.6	15.1	13.4	15.7	18.0	12.8	23.0
Southern Ocean sea surface salinity 2005-2021 in psu (Good et al., 2013)											
subpolar seasonally stratified biome (SPSS)	33.93 ± 6	34.26 ± 6	33.80 ± 6	34.26 ± 2	34.05 ± 3	33.92 ± 1	34.090	34.17 ± 9	34.05 ± 0	33.81 ± 7	34.133
subpolar seasonally stratified	34.30 ± 2	34.58 ± 2	34.17 ± 7	34.53 ± 7	34.38 ± 5	34.25 ± 6	34.388	34.44 ± 5	34.36 ± 1	34.12 ± 1	34.503

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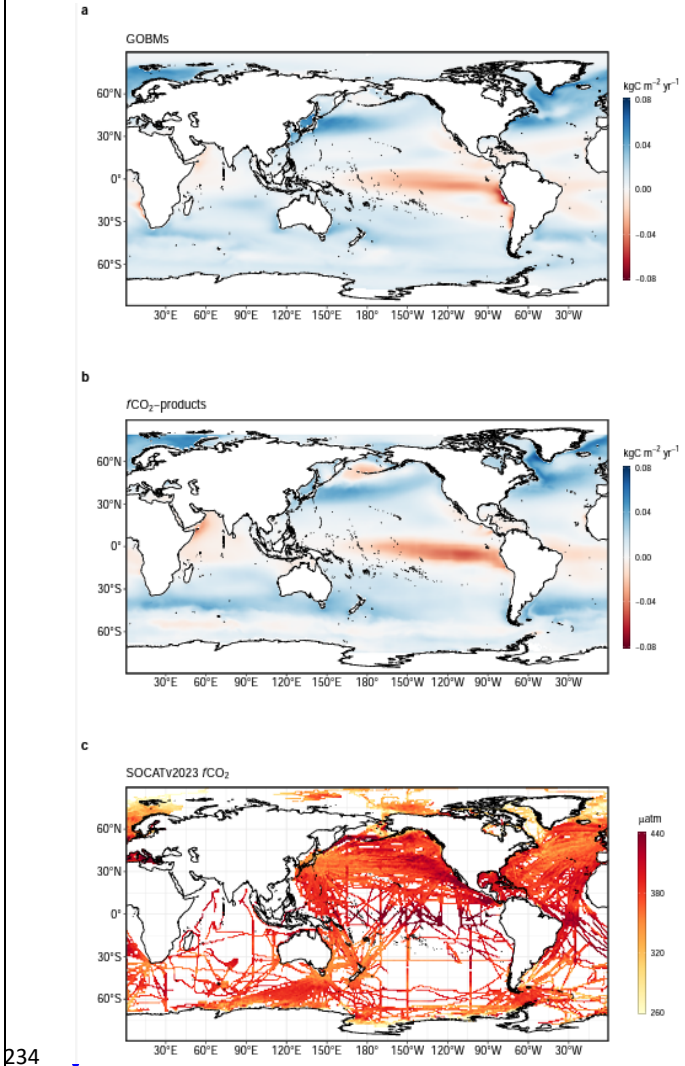
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and subtropic al seasonall y stratified biomes (SPSS+STS S).													
<i>Southern Ocean stratificat ion index 2005- 2021, in kg m-3 (Bourgeoi s et al., 2022, Good et al., 2013).</i>	5.88	5.44	5.94	5.68	6.13	5.97	6.00	5.92	5.11	6.21	5.77		
<i>Surface ocean Revelle factor.</i>													
1997- 2007, unitless (GLODAPv 2.2016, Lauvset et al., 2016)	10.44	10.60	10.31	10.66	10.33	10.72	10.58	10.64	10.33	10.75	10.57		
2005- 2021, unitless (OceanSO DA_v2023 , updated from Gregor and Gruber, 2021)	10.62	10.76	10.50	10.85	10.51	10.92	10.77	10.80	10.48	10.91	10.74		

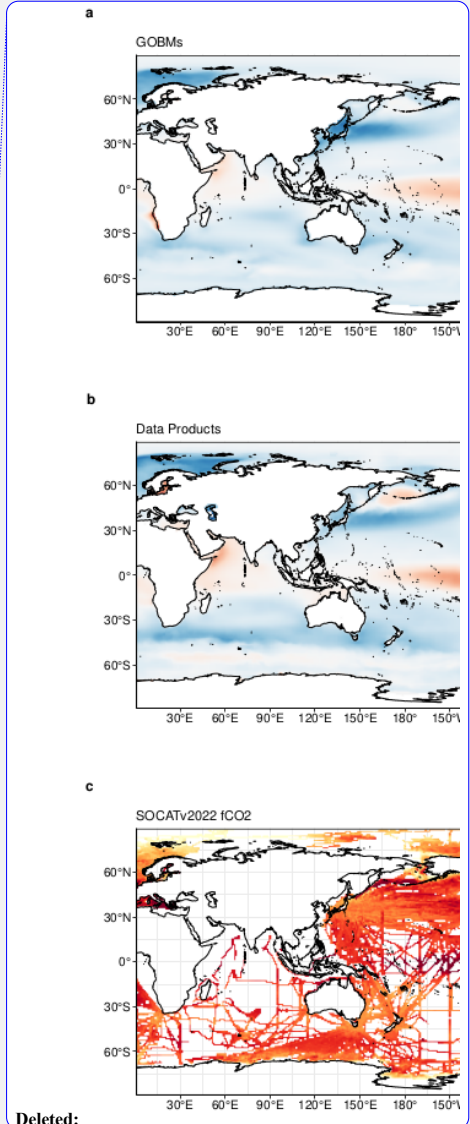
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233 Appendix B. Supplementary Figures



234  
235 **Figure B1.** Ensemble mean air-sea CO<sub>2</sub> flux from a) global ocean biogeochemistry models and b) fCO<sub>2</sub> based  
236 data products, averaged over 2013-2022 period (kgC m<sup>-2</sup> yr<sup>-1</sup>). Positive numbers indicate a flux into the ocean.  
237 c) gridded SOCAT v2023 fCO<sub>2</sub> measurements, averaged over the 2013-2022 period (µatm). In (a) model  
238 simulation A is shown. The fCO<sub>2</sub>-products represent the contemporary flux, i.e. including outgassing of riverine  
239 carbon, which is estimated to amount to 0.65 GtC yr<sup>-1</sup> globally.

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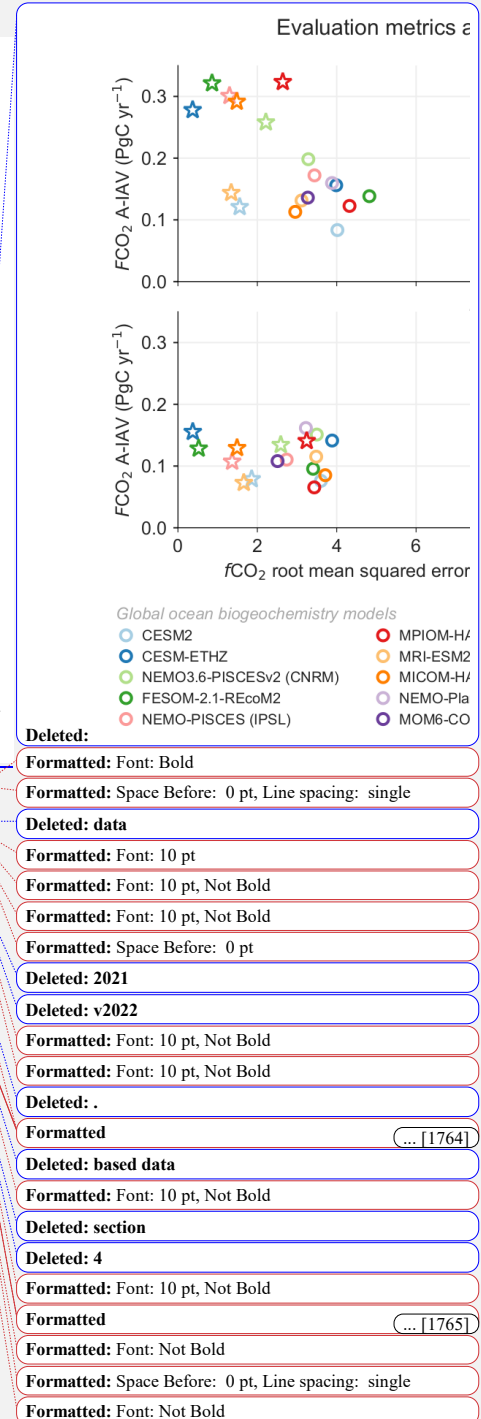
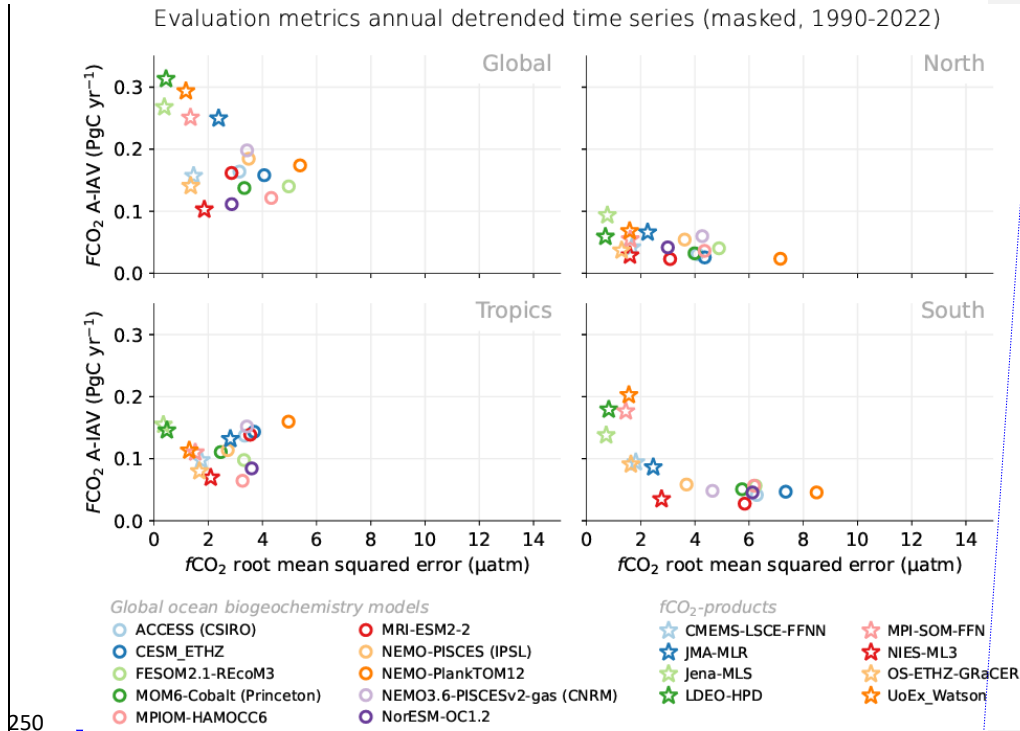
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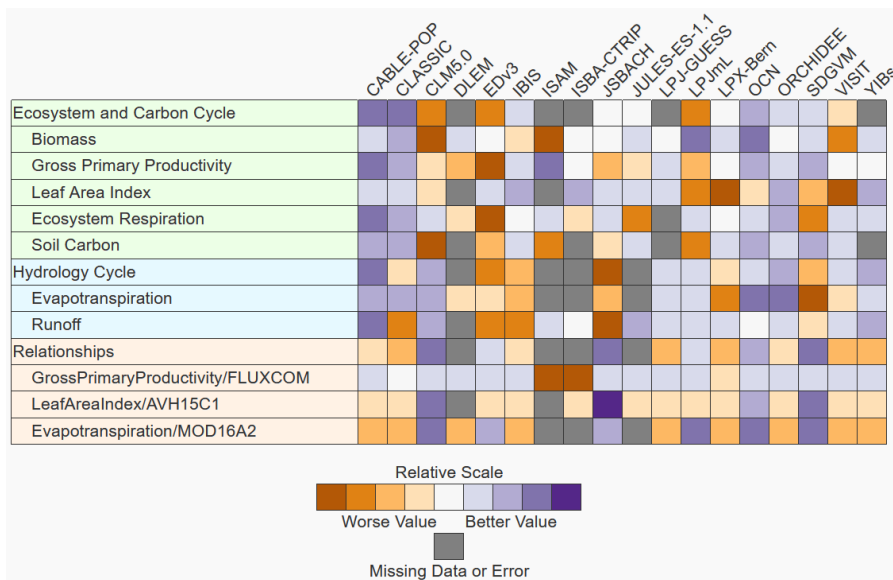
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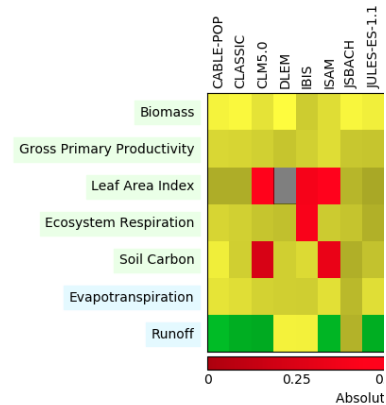




**Figure B2.** Evaluation of the GOBMs and  $f\text{CO}_2$ -products using the root mean squared error (RMSE) for the period 1990 to 2022, between the individual surface ocean  $f\text{CO}_2$  mapping schemes and the SOCAT v2023 database. The y-axis shows the amplitude of the interannual variability of the air-sea  $\text{CO}_2$  flux (A-IAV, taken as the standard deviation of the detrended annual time series). Results are presented for the globe, north ( $>30^\circ\text{N}$ ), tropics ( $30^\circ\text{S}$ - $30^\circ\text{N}$ ), and south ( $<30^\circ\text{S}$ ) for the GOBMs (see legend, circles) and for the  $f\text{CO}_2$ -based data products (star symbols). The  $f\text{CO}_2$ -products use the SOCAT database and therefore are not independent from the data (see Section 2.5.1).



**Figure B3.** Evaluation of the DGVMs using the International Land Model Benchmarking system (ILAMB; Collier et al., 2018). Skill scores relative to other models. The benchmarking is done with observations for vegetation biomass (Santoro and Cartus, 2021; Saatchi et al., 2011; Thurner et al. 2014), GPP and ecosystem respiration (Reichstein et al., 2007; Lasslop et al., 2010; Knauer et al., 2018; Jung et al., 2017; Tramontana et al., 2016; Alemohammad et al., 2017), leaf area index (Vermote, 2019; Claverie et al., 2016; De Kauwe et al., 2011; Myneni et al., 1997), soil carbon (Hugelius et al., 2013; Fischer et al., 2008), evapotranspiration (De Kauwe et al., 2011; Martens et al., 2017; Miralles et al., 2011; Mu et al., 2011), and runoff (Dai and Trenberth, 2002; Hobeichi et al., 2019; Hobeichi et al., 2020). Metrics include relationships between carbon cycle variables, precipitation (Adler et al., 2003) and temperature (Harris et al., 2014). For each model-observation comparison a series of error metrics are calculated, scores are then calculated as an exponential function of each error metric, and finally for each variable the multiple scores from different metrics and observational datasets are combined to give the overall variable scores. Overall variable scores increase from 0 to 1 with improvements in model performance. The set of error metrics vary with dataset and can include metrics based on the period mean, bias, root mean squared error, spatial distribution, interannual variability, and seasonal cycle. The relative skill score shown is a Z-score, which indicates in units of standard deviation the model scores relative to the multi-model mean score for a given variable. Grey boxes represent missing model data.



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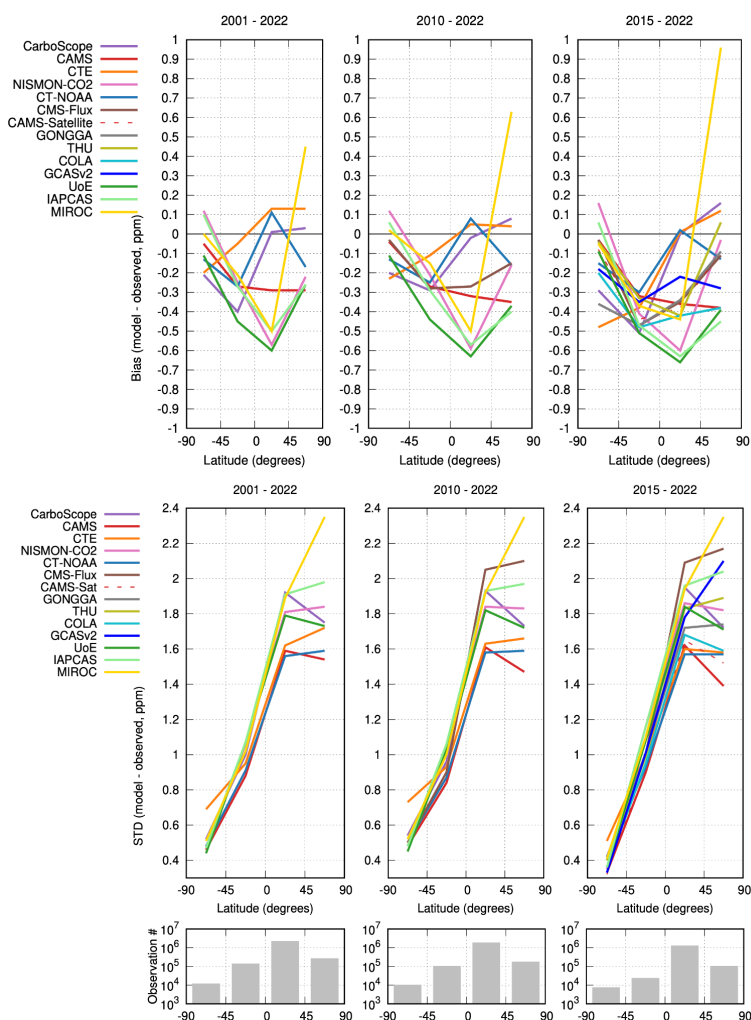
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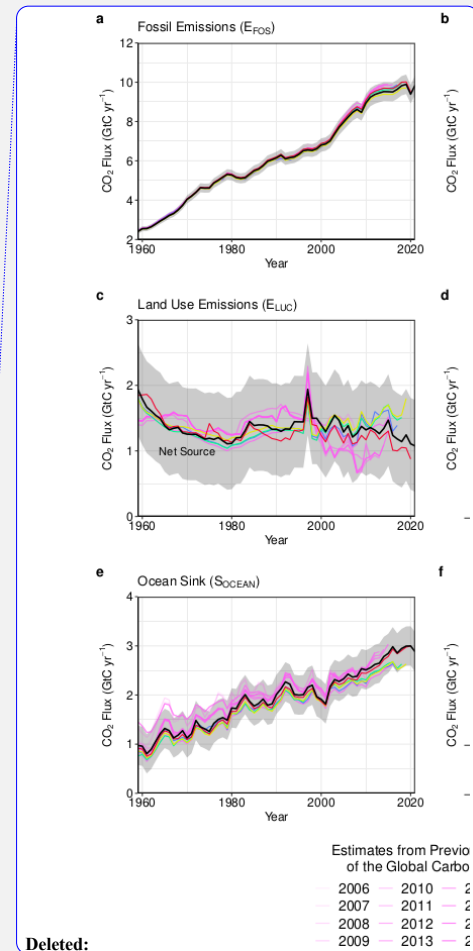
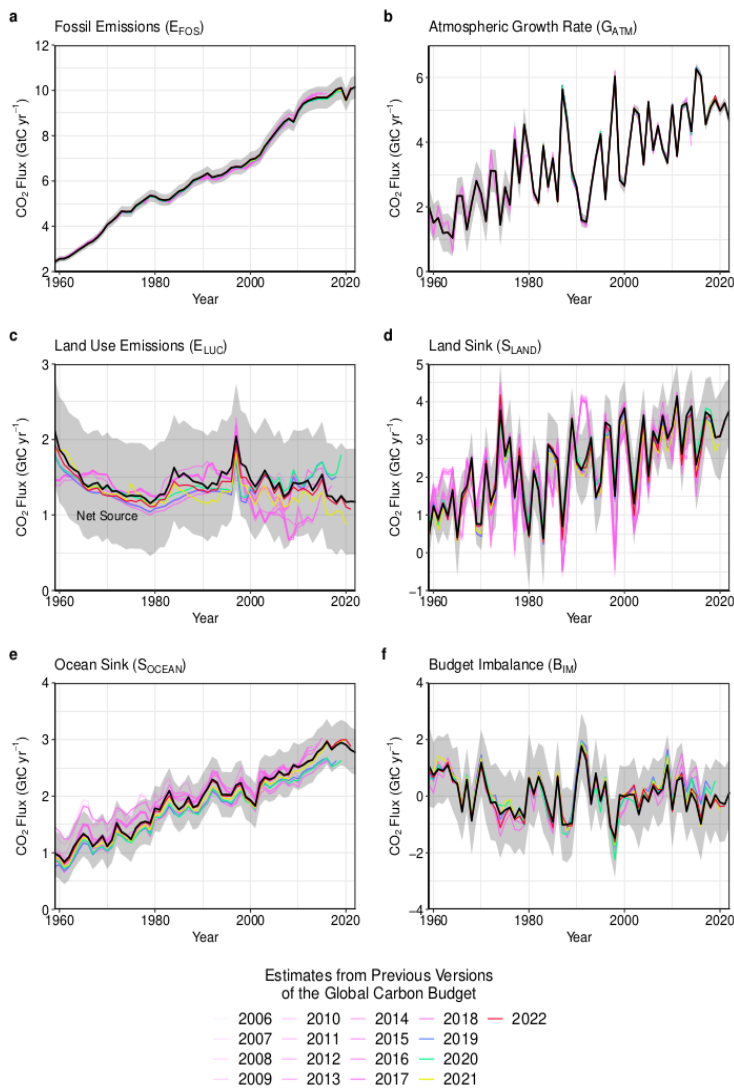
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**Figure B4.** Evaluation of the atmospheric inversion products. The mean of the model minus observations is shown for four latitude bands in three periods: (first panel) 2001-2022, (second panel) 2010-2012, (third panel) 2015-2023. The 14 systems are compared to independent CO<sub>2</sub> observations from aircraft over many places of the world between 2 and 7 km above sea level. Aircraft measurements archived in the Cooperative Global Atmospheric Data Integration Project (Schuldt et al. 2022, Schuldt et al. 2023) from sites, campaigns or programs that have not been assimilated and cover at least 9 months (except for SH programs) between 2001 and 2022, have been used to compute the biases (top row) and their standard deviations (middle row) in four 45° latitude bins. Land and ocean data are used without distinction, and observation density varies strongly with latitude and time as seen on the lower panels.



**Figure B5.** Comparison of the estimates of each component of the global carbon budget in this study (black line) with the estimates released annually by the GCP since 2006. Grey shading shows the uncertainty bounds representing  $\pm 1$  standard deviation of the current global carbon budget, based on the uncertainty assessments described in Appendix C. CO<sub>2</sub> emissions from (a) fossil CO<sub>2</sub> emissions excluding cement carbonation ( $E_{FOS}$ ), and (b) land-use change ( $E_{LUC}$ ), as well as their partitioning among (c) the atmosphere ( $G_{ATM}$ ), (d) the land ( $S_{LAND}$ ), and (e) the ocean ( $S_{OCEAN}$ ). See legend for the corresponding years, and Tables 3 and A8 for description

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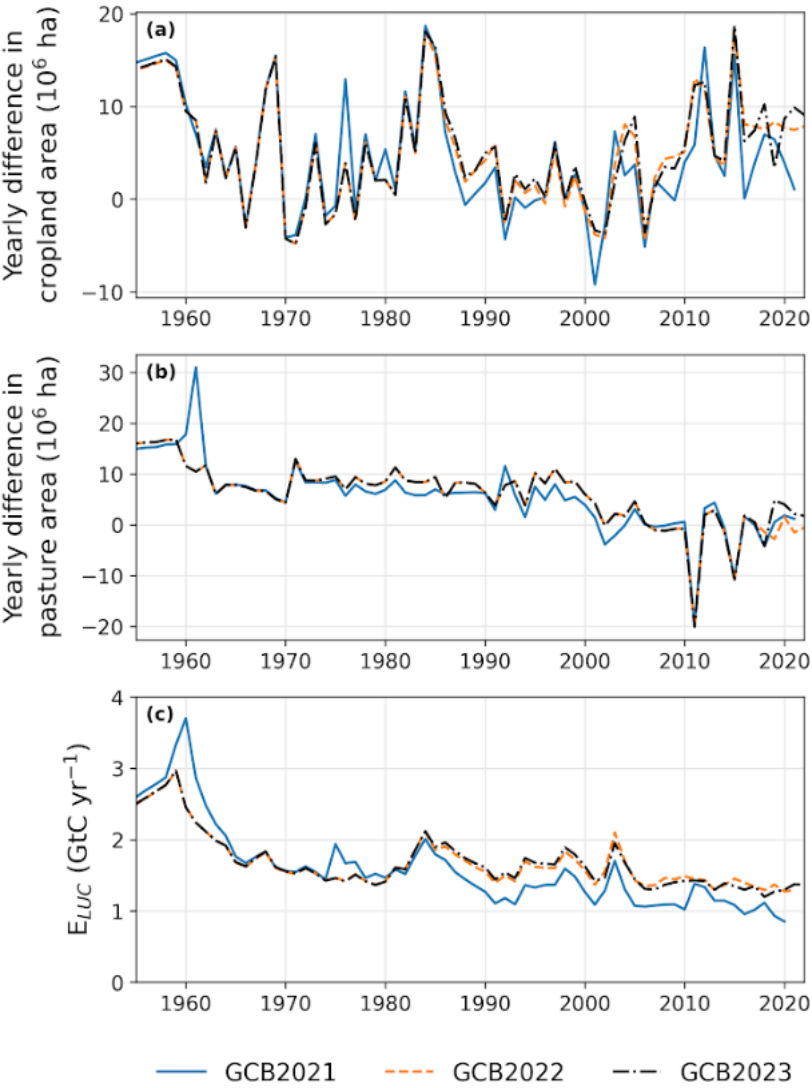
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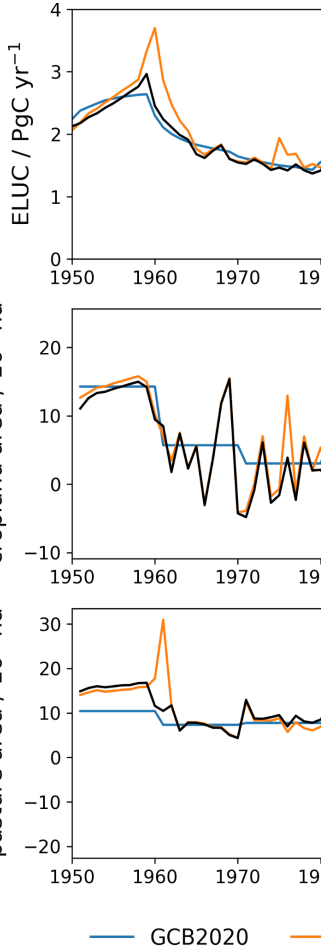
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of changes in methodology. The budget year corresponds to the year when the budget was first released. All values are in GtC yr<sup>-1</sup>.



**Figure B6.** Differences in the HYDE/LUH2 land-use forcing used for the global carbon budgets GCB2021 (Friedlingstein et al., 2022a), GCB2022 (Friedlingstein et al., 2022b), and GCB2023 (this paper). Shown are year-to-year changes in cropland area (top panel) and pasture area (middle panel). To illustrate the relevance of the update in the land-use forcing to the recent trends in ELUC, the bottom panel shows the land-use emission



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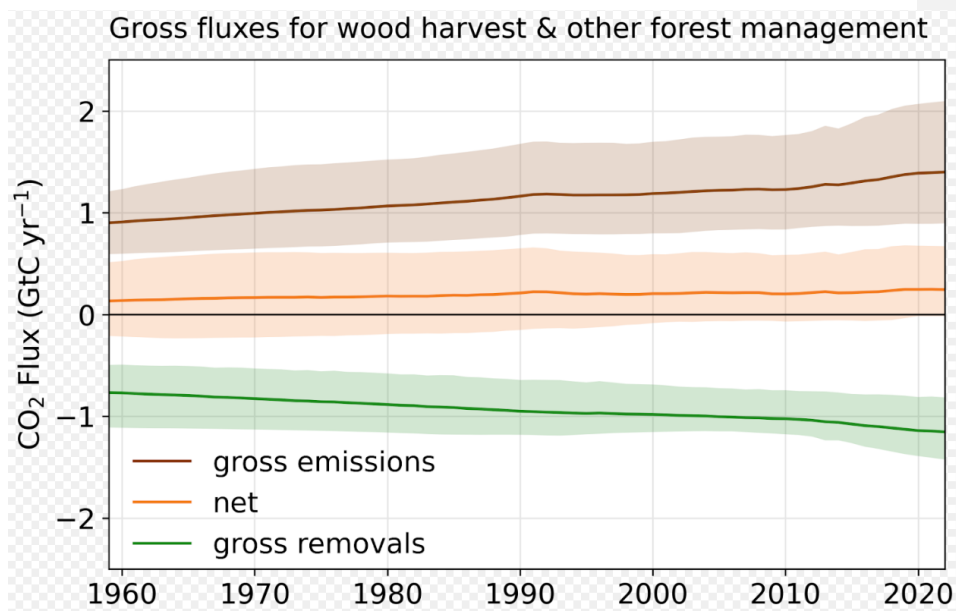
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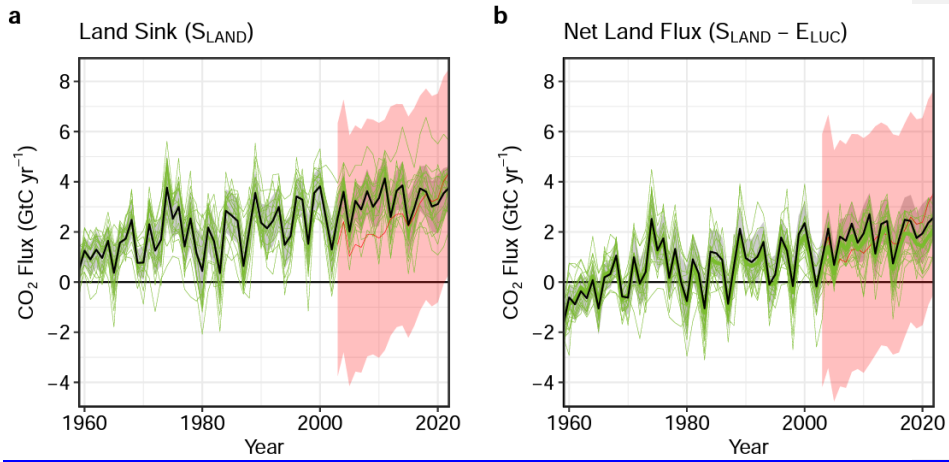
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395 estimate from the bookkeeping model BLUE (original model output, i.e., excluding emissions from peat fire and  
396 peat drainage).

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**Figure B7:** Split of net fluxes from wood harvest and other forest management into gross emissions and gross removals. Solid lines denote the average of the three bookkeeping models and shaded areas the full range (min-max) of the bookkeeping model estimates.



**Figure B8.** As Figure 8 but with the inclusion of CARDAMOM) (a) The land CO<sub>2</sub> sink ( $S_{\text{LAND}}$ ) estimated by individual DGVMs estimates (green), as well as the budget estimate (black with  $\pm 1\sigma$  uncertainty), which is the average of all DGVMs. (b) Total atmosphere-land CO<sub>2</sub> fluxes ( $S_{\text{LAND}} - E_{\text{LUC}}$ ). Panel (b) also includes an estimate for the total land flux for individual DGVMs (thin green lines) and their multi-model mean (thick green line). The red line is the mean CARDAMOM result and uncertainty range in pink.



**Figure B9.** Fire carbon emissions for the months January-September for each year 2003-2023 from two global fire emissions products. **(Top row)** Global emissions. **(Middle row)** Emissions for the northern hemisphere extratropics ( $>30^{\circ}$  N), tropics ( $30^{\circ}$  N- $30^{\circ}$  S) and southern extratropics ( $>30^{\circ}$  S). **(Bottom row)** Emissions by RECCAP2 region. The Global Fire Assimilation System (GFAS; Di Giuseppe et al., 2018) (**left column**) and the Global Fire Emissions Database (GFED, version 4.1s; van der Werf et al., 2017) (**right column**) are among the most widely applied global fire emissions products based on satellite remote sensing of fire. GFED relies on the post-fire detection of burned areas combined with fuel consumption factors. GFAS relies on the detection of thermal energy release during active fires.

422 **Appendix C. Extended Methodology**

423 **C.1 Methodology Fossil Fuel CO<sub>2</sub> emissions (E<sub>FOS</sub>)**

424 **C.1.1 Cement carbonation**

425 From the moment it is created, cement begins to absorb CO<sub>2</sub> from the atmosphere, a process known as ‘cement  
426 carbonation’. We estimate this CO<sub>2</sub> sink, from 1931 onwards, as the average of two studies in the literature (Cao  
427 et al., 2020; Guo et al., 2021, [extended by Huang et al., 2023](#)). The Global Cement and Concrete Association  
428 reports a much lower carbonation rate, but this is based on the highly conservative assumption of 0% mortar  
429 (GCCA, 2021). Modelling cement carbonation requires estimation of a large number of parameters, including  
430 the different types of cement material in different countries, the lifetime of the structures before demolition, of  
431 cement waste after demolition, and the volumetric properties of structures, among others (Xi et al., 2016).  
432 Lifetime is an important parameter because demolition results in the exposure of new surfaces to the  
433 carbonation process. The main reasons for differences between the two studies appear to be the assumed  
434 lifetimes of cement structures and the geographic resolution, but the uncertainty bounds of the two studies  
435 overlap.

436 **C.1.2 Emissions embodied in goods and services**

437 CDIAC, UNFCCC, and BP national emission statistics ‘include greenhouse gas emissions and removals taking  
438 place within national territory and offshore areas over which the country has jurisdiction’ (Rypdal et al., 2006),  
439 and are called territorial emission inventories. Consumption-based emission inventories allocate emissions to  
440 products that are consumed within a country, and are conceptually calculated as the territorial emissions minus  
441 the ‘embodied’ territorial emissions to produce exported products plus the emissions in other countries to  
442 produce imported products (Consumption = Territorial – Exports + Imports). Consumption-based emission  
443 attribution results (e.g. Davis and Caldeira, 2010) provide additional information to territorial-based emissions  
444 that can be used to understand emission drivers (Hertwich and Peters, 2009) and quantify emission transfers by  
445 the trade of products between countries (Peters et al., [2011a](#)). The consumption-based emissions have the same  
446 global total, but reflect the trade-driven movement of emissions across the Earth's surface in response to human  
447 activities. We estimate consumption-based emissions from 1990-2020 by enumerating the global supply chain  
448 using a global model of the economic relationships between economic sectors within and between every country  
449 (Andrew and Peters, 2013; Peters et al., [2011b](#)). Our analysis is based on the economic and trade data from the  
450 Global Trade and Analysis Project (GTAP; Narayanan et al., 2015), and we make detailed estimates for the  
451 years 1997 (GTAP version 5), 2001 (GTAP6), and 2004, 2007, 2011, and 2014 (GTAP10.0a), covering 57  
452 sectors and 141 countries and regions. The detailed results are then extended into an annual time series from  
453 1990 to the latest year of the Gross Domestic Product (GDP) data (2020 in this budget), using GDP data by  
454 expenditure in current exchange rate of US dollars (USD; from the UN National Accounts main Aggregates  
455 database; UN, [2022](#)) and time series of trade data from GTAP (based on the methodology in Peters et al.,  
456 [2011b](#)). We estimate the sector-level CO<sub>2</sub> emissions using the GTAP data and methodology, add the flaring and  
457 cement emissions from our fossil CO<sub>2</sub> dataset, and then scale the national totals (excluding bunker fuels) to  
458 match the emission estimates from the carbon budget. We do not provide a separate uncertainty estimate for the

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consumption-based emissions, but based on model comparisons and sensitivity analysis, they are unlikely to be significantly different than for the territorial emission estimates (Peters et al., 2012b).

### C.1.3 Uncertainty assessment for $E_{FOS}$

We estimate the uncertainty of the global fossil CO<sub>2</sub> emissions at  $\pm 5\%$  (scaled down from the published  $\pm 10\%$  at  $\pm 2\sigma$  to the use of  $\pm 1\sigma$  bounds reported here; Andres et al., 2012). This is consistent with a more detailed analysis of uncertainty of  $\pm 8.4\%$  at  $\pm 2\sigma$  (Andres et al., 2014) and at the high-end of the range of  $\pm 5\text{--}10\%$  at  $\pm 2\sigma$  reported by (Ballantyne et al., 2015). This includes an assessment of uncertainties in the amounts of fuel consumed, the carbon and heat contents of fuels, and the combustion efficiency. While we consider a fixed uncertainty of  $\pm 5\%$  for all years, the uncertainty as a percentage of emissions is growing with time because of the larger share of global emissions from emerging economies and developing countries (Marland et al., 2009). Generally, emissions from mature economies with good statistical processes have an uncertainty of only a few per cent (Marland, 2008), while emissions from strongly developing economies such as China have uncertainties of around  $\pm 10\%$  (for  $\pm 1\sigma$ ; Gregg et al., 2008; Andres et al., 2014). Uncertainties of emissions are likely to be mainly systematic errors related to underlying biases of energy statistics and to the accounting method used by each country.

### C.1.4 Growth rate in emissions

We report the annual growth rate in emissions for adjacent years (in percent per year) by calculating the difference between the two years and then normalising to the emissions in the first year:  $(E_{FOS}(t+1) - E_{FOS}(t)) / E_{FOS}(t) \times 100\%$ . 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<sup>-1</sup> ( $1/366$ ) and causes calculated growth rates to go up approximately  $0.3\%$  if the first year is a leap year and down  $0.3\%$  if the second year is a leap year.

The relative growth rate of  $E_{FOS}$  over time periods of greater than one year can be rewritten using its logarithm equivalent as follows:

$$\frac{1}{E_{FOS}} \frac{dE_{FOS}}{dt} = \frac{d(\ln E_{FOS})}{dt} \quad (2)$$

Here we calculate relative growth rates in emissions for multi-year periods (e.g. a decade) by fitting a linear trend to  $\ln(E_{FOS})$  in Eq. (2), reported in percent per year.

### C.1.5 Emissions projection for 2023

To gain insight on emission trends for 2023, we provide an assessment of global fossil CO<sub>2</sub> emissions,  $E_{FOS}$ , by combining individual assessments of emissions for China, USA, the EU, and India (the four countries/regions with the largest emissions), and the rest of the world.

The methods are specific to each country or region, as described in detail below.

**China:** We use a regression between monthly data for each fossil fuel and cement, and annual data for consumption of fossil fuels / production of cement to project full-year growth in fossil fuel consumption and cement production. The monthly data for each product consists of the following:

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501 Coal: Production data from the National Bureau of Statistics (NBS), plus net imports from the China  
 502 Customs Administration (i.e., gross supply of coal, not including inventory changes), adjusted  
 503 using monthly production data for thermal electricity, crude steel, pig iron, coke and cement from  
 504 NBS.  
 505 Oil: Production data from NBS, plus net imports from the China Customs Administration (i.e., gross  
 506 supply of oil, not including inventory changes)  
 507 Natural gas: Same as for oil  
 508 Cement: Production data from NBS

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 Oil

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509 For oil, we use data for production and net imports of refined oil products rather than crude oil. This choice is  
 510 made because refined products are one step closer to actual consumption, and because crude oil can be subject  
 511 to large market-driven and strategic inventory changes that are not captured by available monthly data.  
 512 Furthermore, refinery output in 2022 was atypically low through August of that year compared to the rest of the  
 513 year, which results in very high growth figures for the 2023 data compared to what one can likely expect for the  
 514 last four months of this year. The estimate has been adjusted down by 0.8 percentage points to account for this,  
 515 corresponding to how much lower the ratio of January-August and September-December refinery output was in  
 516 2022 compared to the average for 2014-2022.

517 For each fuel and cement, we make a Bayesian linear regression between year-on-year cumulative growth in  
 518 supply (production for cement) and full-year growth in consumption (production for cement) from annual  
 519 consumption data. In the regression model, the growth rate in annual consumption (production for cement) is  
 520 modelled as a regression parameter multiplied by the cumulative year-on-year growth rate from the monthly  
 521 data through August of each year for past years (through 2022). We use broad Gaussian distributions centered  
 522 around 1 as priors for the ratios between annual and through August growth rates. We then use the posteriors for  
 523 the growth rates together with cumulative monthly supply/production data through August of 2023 to produce a  
 524 posterior predictive distribution for the full-year growth rate for fossil fuel consumption / cement production in  
 525 2023.

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526 If the growth in supply/production through August were an unbiased estimate of the full-year growth in  
 527 consumption/production, the posterior distribution for the ratio between the monthly and annual growth rates  
 528 would be centered around 1. However, in practice the ratios are different from 1 (in most cases below 1). This is  
 529 a result of various biasing factors such as uneven evolution in the first and second half of each year, inventory  
 530 changes that are somewhat anti-correlated with production and net imports, differences in statistical coverage,  
 531 and other factors that are not captured in the monthly data.

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532 For fossil fuels, the mean of the posterior distribution is used as the central estimate for the growth rate in 2023,  
 533 while the edges of a 68% credible interval (analogous to a 1-sigma confidence interval) are used for the upper  
 534 and lower bounds.

**Deleted:** For cement, the evolution from January to July has been highly atypical owing to the ongoing turmoil in the construction sector, and the results of the regression analysis are heavily biased by equally atypical but different dynamics in 2021. For this reason, we use an average of the results of the regression analysis and the plain growth in cement production through July 2022, since this results in a growth rate that seems more plausible and in line with where the cumulative cement production appears to be headed at the time of writing.

535 USA: We use emissions estimated by the U.S. Energy Information Administration (EIA) in their Short-Term  
 536 Energy Outlook (STEO) for emissions from fossil fuels to get both YTD and a full year projection (EIA, 2022).  
 537 The STEO also includes a near-term forecast based on an energy forecasting model which is updated monthly  
 538 (last update with preliminary data through August 2023), and takes into account expected temperatures,

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household expenditures by fuel type, energy markets, policies, and other effects. We combine this with our estimate of emissions from cement production using the monthly U.S. cement clinker production data from USGS for January–July 2023, assuming changes in clinker production over the first part of the year apply throughout the year.

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**India:** We use monthly emissions estimates for India updated from Andrew (2020b) through July/August 2023. These estimates are derived from many official monthly energy and other activity data sources to produce direct estimates of national CO<sub>2</sub> emissions, without the use of proxies. Emissions from coal are then extended to September using a regression relationship based on power generated from coal, coal dispatches by Coal India Ltd., the composite PMI, time, and days per month. For the last 3–5 months of the year, each series is extrapolated assuming typical (pre-2019) trends.

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**EU:** We use a refinement to the methods presented by Andrew (2021), deriving emissions from monthly energy data reported by Eurostat. Some data gaps are filled using data from the Joint Organisations Data Initiative (JODI, 2022). Sub-annual cement and cement-clinker production data are limited, but data for Germany, Poland and Spain, the three largest producers, suggest a decline of over 10%. For fossil fuels this provides estimates through July. We extend coal emissions through September using a regression model built from generation of power from hard coal, power from brown coal, and the number of working days in Germany, the biggest coal consumer in the EU. These are then extended through the end of the year assuming typical trends. We extend oil emissions by building a regression model between our monthly CO<sub>2</sub> estimates and oil consumption reported by the EIA for Europe in its Short-Term Energy Outlook (September edition), and then using this model with EIA’s monthly forecasts. For natural gas, the strong seasonal signal allows the use of the bias-adjusted Holt-Winters exponential smoothing method (Chatfield, 1978), although this comes with larger uncertainty given the unusual energy situation in Europe in 2022–23.

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**Rest of the world:** We use the close relationship between the growth in GDP and the growth in emissions (Raupach et al., 2007) to project emissions for the current year. This is based on a simplified Kaya Identity, whereby E<sub>FOS</sub> (GtC yr<sup>-1</sup>) is decomposed by the product of GDP (USD yr<sup>-1</sup>) and the fossil fuel carbon intensity of the economy (I<sub>FOS</sub>; GtC USD<sup>-1</sup>) as follows:

$$E_{FOS} = GDP \times I_{FOS} \quad (3)$$

Taking a time derivative of Equation (3) and rearranging gives:

$$\frac{1}{E_{FOS}} \frac{dE_{FOS}}{dt} = \frac{1}{GDP} \frac{dGDP}{dt} + \frac{1}{I_{FOS}} \frac{dI_{FOS}}{dt} \quad (4)$$

where the left-hand term is the relative growth rate of E<sub>FOS</sub>, and the right-hand terms are the relative growth rates of GDP and I<sub>FOS</sub>, respectively, which can simply be added linearly to give the overall growth rate.

The I<sub>FOS</sub> is based on GDP in constant PPP (Purchasing Power Parity) from the International Energy Agency (IEA) up to 2017 (IEA/OECD, 2019) and extended using the International Monetary Fund (IMF) growth rates through 2022 (IMF, 2023). Interannual variability in I<sub>FOS</sub> is the largest source of uncertainty in the GDP-based emissions projections. We thus use the standard deviation of the annual I<sub>FOS</sub> for the period 2013–2022 as a measure of uncertainty, reflecting a ±1σ as in the rest of the carbon budget. For rest-of-world oil emissions growth, we use the global oil demand forecast published by the EIA less our projections for the other four

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regions, and estimate uncertainty as the maximum absolute difference over the period available for such forecasts using the specific monthly edition (e.g. August) compared to the first estimate based on more solid data in the following year (April).

**World:** The global total is the sum of each of the countries and regions.

## C.2 Methodology CO<sub>2</sub> emissions from land-use, land-use change and forestry (ELUC)

The net CO<sub>2</sub> flux from land-use, land-use change and forestry (ELUC, called land-use change emissions in the rest of the text) includes CO<sub>2</sub> fluxes from deforestation, afforestation, logging and forest degradation (including harvest activity), shifting cultivation (cycle of cutting forest for agriculture, then abandoning), and regrowth of forests following wood harvest or abandonment of agriculture. Land-management activities are only partly included in our land-use change emissions estimates (Table A1). Emissions from peat burning and peat drainage are added from external datasets (see Appendix C.2.1 below). Some land-use change and land-management activities cause emissions of CO<sub>2</sub> to the atmosphere, while others remove CO<sub>2</sub> from the atmosphere. ELUC is the net sum of emissions and removals due to all anthropogenic activities considered. Our annual estimates for 1960-2022 are provided as the average of results from three bookkeeping approaches (Appendix C.2.1 below): an estimate using the Bookkeeping of Land Use Emissions model (Hansis et al., 2015; hereafter BLUE), one using the compact Earth system model OSCAR (Gasser et al., 2020), and an estimate published by Houghton and Castanho (2023; hereafter H&C2023, an updated version of the formerly used model H&N2017). BLUE and OSCAR are updated with new land-use forcing data covering the time period until 2022. All three data sets are extrapolated to provide a projection for 2023 (see Appendix C.2.5 below). In addition, we use results from Dynamic Global Vegetation Models (DGVMs; see Appendix 2.5 and Table 4) to help quantify the uncertainty in ELUC (Appendix C.2.4), and thus better characterise our understanding of the robustness of annual estimates and trends. Note that in this budget, we follow the scientific ELUC definition as used by global carbon cycle models, which counts fluxes due to environmental changes on managed land towards S<sub>LAND</sub>, as opposed to the national greenhouse gas inventories under the UNFCCC, most of which include them in ELUC and thus often report smaller land-use emissions (Grassi et al., 2018; Petrescu et al., 2020). Following the methodology of Grassi et al. (2023), we provide harmonised estimates of the two approaches further below (see Appendix C.2.3).

### C.2.1 Bookkeeping models

CO<sub>2</sub> emissions and removals from land-use change are calculated by three bookkeeping models. These are based on the original bookkeeping approach of Houghton (2003), which keeps track of the carbon stored in vegetation and soils before and after a land-use change event (transitions between various natural vegetation types, croplands, and pastures). Literature-based response curves describe decay of vegetation and soil carbon, including transfer to product pools of different lifetimes, as well as carbon uptake due to regrowth. In addition, the bookkeeping models represent 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 harvests. BLUE and H&C2023 exclude the transient response of land ecosystems to changes in climate, atmospheric CO<sub>2</sub>, and other environmental factors, and base the carbon densities of soil and vegetation on contemporary data from literature and inventory data. Since carbon densities thus remain fixed over time, the additional sink capacity that ecosystems provide in response to CO<sub>2</sub>-fertilisation and some other environmental changes are not

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686 captured by these models (Pongratz et al., 2014). On the contrary, OSCAR includes this transient response, and  
 687 it follows a theoretical framework (Gasser and Ciais, 2013) that allows separating bookkeeping land-use  
 688 emissions and the loss of additional sink capacity. Only the former is included here, while the latter is discussed  
 689 in Appendix D4. The bookkeeping models differ in (1) computational units (spatially explicit treatment of land-  
 690 use change [at 0.25° resolution](#) for BLUE, country-level for [H&C2023](#) and OSCAR), (2) processes represented  
 691 (see Table A1), and (3) carbon densities assigned to vegetation and [soils for different types of vegetation](#)  
 692 (literature-based for BLUE and [H&C2023](#), calibrated to DGVMs for OSCAR). A notable difference between  
 693 models exists with respect to the treatment of shifting cultivation: [H&C2023 assumes that forest loss—derived](#)  
 694 [from the Global Forest Resources Assessment \(FRA; FAO, 2020\)—in excess of increases in cropland and](#)  
 695 [pastures—derived from FAOSTAT \(FAO, 2021\)—represents an increase in shifting cultivation. If the excess](#)  
 696 [loss of forests in a year is negative, it is assumed that shifting cultivation is returned to forest. Historical areas in](#)  
 697 [shifting cultivation are defined taking into account country-based estimates of areas in fallow in 1980](#)  
 698 [\(FAO/UNEP, 1981\) and expert opinion \(from Heinemann et al., 2017\). In contrast, BLUE and OSCAR include](#)  
 699 [subgrid-scale transitions between all vegetation types. Furthermore, H&C2023 assumes conversion of natural](#)  
 700 [grasslands to pasture, while BLUE and OSCAR allocate pasture transitions proportionally to all natural](#)  
 701 [vegetation that exists in a grid-cell. This is one reason for generally higher emissions in BLUE and OSCAR. In](#)  
 702 [this GCB, we split CO<sub>2</sub> emissions into emissions from permanent deforestation and from deforestation for](#)  
 703 [shifting cultivation. Similarly, we separate the forest \(re-\)growth estimates into \(re-\)growth from af/reforestation](#)  
 704 [and from regrowth associated with shifting cultivation. This distinction is insightful with regard to the levers on](#)  
 705 [the reduction of net emissions: as deforestation for shifting cultivation is only temporary, the associated CO<sub>2</sub>](#)  
 706 [emissions cannot easily be avoided without compromising the CO<sub>2</sub> removals from regrowth in shifting](#)  
 707 [cultivation cycles. By contrast, permanent deforestation is typically not directly related to af/reforestation.](#)  
 708 [Stopping deforestation for permanent agricultural expansion and increasing the forest area provide two](#)  
 709 [independent paths towards net emissions reduction.](#)  
 710 Bookkeeping models do not directly capture carbon emissions from [the organic layers of drained peat soils nor](#)  
 711 [from peat fires. Particularly the latter can create large emissions and interannual variability due to synergies of](#)  
 712 [land-use and climate variability in equatorial Southeast Asia, particularly during El-Niño events. To correct for](#)  
 713 [this, we add peat fire emissions based on the Global Fire Emission Database \(GFED4s; van der Werf et al.,](#)  
 714 [2017\) to the bookkeeping models' output. Peat fire emissions are calculated by multiplying the mass of dry](#)  
 715 [matter emitted by peat fires with the C emission factor for peat fires indicated in the GFED4s database.](#)  
 716 [Emissions from deforestation and degradation fires \(used for extrapolating the H&C2023 data beyond 2020 and](#)  
 717 [to derive the 2023 projection of all three models; see below\) are calculated analogously. The satellite-derived](#)  
 718 [estimates of peat fire emissions start in 1997 only. We thus follow the approach by Houghton and Nassikas](#)  
 719 [\(2017\) for earlier years, which linearly ramps up from zero emissions in 1980 to 0.04 GtC yr<sup>-1</sup> in 1996,](#)  
 720 [reflecting the onset of major clearing of peatlands in equatorial Southeast Asia in the 1980s. Similarly, we add](#)  
 721 [estimates of peat drainage emissions, combining estimates from three spatially explicit datasets. We employ](#)  
 722 [FAO peat drainage emissions 1990–2020 from croplands and grasslands \(Conchedda and Tubiello, 2020\), peat](#)  
 723 [drainage emissions 1700–2010 from simulations with the DGVM ORCHIDEE-PEAT \(Qiu et al., 2021\), and](#)  
 724 [peat drainage emissions 1701–2021 from simulations with the DGVM LPX-Bern v1.5 \(Lienert and Joos, 2018;](#)  
 725 [Müller and Joos, 2021\), the latter applying the updated LUH2-GCB2023 forcing as also used by BLUE,](#)

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- Deleted: N2017, introduced for the GCB2021 (Friedlingstein et al., 2022) changed the approach over the earlier H&N2017 version: H&N2017 had assumed the "excess loss" of tropical forests (i.e., when
- Deleted: ) indicated a forest loss larger than the increase in agricultural areas from FAO (FAOSTAT 2021) resulted from converting forests to croplands at the same time older croplands were abandoned. Those abandoned croplands began to recover to forests after 15 years. The updated H&N2017 now assumes that forest loss
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OSCAR, and the DGVMs. The LPX-Bern industrial period simulations started from a transient run over the last deglaciation (~20,050 to 1700 AD) following Müller and Joos (2020) and are forced by changes in climate, atmospheric CO<sub>2</sub>, nitrogen deposition/input, and land-use changes. Simulations were done with/without prescribing the human land-use changes since 1700 AD, the difference of which yields anthropogenic peat drainage emissions. Peat carbon is stored in (i) active peatlands, (ii) former peatlands (“natural”), and (iii) former peatlands under anthropogenic use. We adopt the average of the two CO<sub>2</sub> emission cases of Müller and Joos (2021) by assuming that half of the peat carbon is lost to the atmosphere immediately after ecosystem or land-use transformation of active to former peatland, while the rest is decaying slowly, pending on local temperature and soil moisture. The LPX-Bern peat drainage emissions show a very high emission peak in Russia in 1959 followed by very low emissions in 1960. This peak can be attributed to an artefact in the HYDE3.3 dataset (Friedlingstein et al. 2022a), which was corrected for Brazil and the Democratic Republic of the Congo in GCB2022 (Friedlingstein et al. 2022b) but remains for Russia where it strongly impacts the LPX-Bern peat drainage estimates in 1959 and 1960. To correct for this unrealistic peak, we replace the LPX-Bern peat drainage emissions in Russia in 1959 and 1960 by the average of the estimates in 1958 and 1961. FAO data are extrapolated to 1850–2022 by keeping the post-2020 emissions constant at 2020 levels, and by linearly increasing tropical peat drainage emissions between 1980 and 1990 starting from 0 GtC yr<sup>-1</sup> in 1980, (consistent with H&N2017’s assumption, Houghton and Nassikas, 2017), and by keeping pre-1990 emissions from the often old drained areas of the extra-tropics constant at 1990 emission levels. ORCHIDEE-PEAT data are extrapolated to 2011–2022 by replicating the average emissions in 2000–2010 (pers. comm. C. Qiu), and LPX-Bern data for 2022 are obtained by replicating the 2021 estimate. Further, ORCHIDEE-PEAT only provides peat drainage emissions north of 30°N, and thus we fill the regions south of 30°N by the average peat drainage emissions from FAO and LPX-Bern. Peat drainage emissions are calculated as the average of the estimates from the three different peat drainage datasets. The net E<sub>LUC</sub> values indicated in the manuscript are the sum of E<sub>LUC</sub> estimates from bookkeeping models, peat fire emissions, and peat drainage emissions.

The three bookkeeping estimates used in this study differ with respect to the land-use change data used to drive the models. H&N2023 base their estimates directly on the Forest Resource Assessment (FRA) of the FAO, which provides statistics on forest-area change and management at intervals of five years currently updated until 2020 (FAO, 2020). The data is based on country reporting to FAO and may include remote-sensing information in more recent assessments. Changes in land use other than forests are based on annual, national changes in cropland and pasture areas reported by the FAO (FAO, 2021). On the other hand, BLUE uses the harmonised land-use change data LUH2-GCB2023 covering the period 850–2022 (an update to the previously released LUH2 v2h dataset; Hurtt et al., 2017; Hurtt et al., 2020), which was also used as input to the DGVMs (Appendix C.2.2). LUH2-GCB2023 provides land-use change data at 0.25° spatial resolution based on the FAO data (as described in Appendix C.2.2) as well as the HYDE3.3 dataset (Klein Goldewijk et al., 2017a, 2017b), considering subgrid-scale transitions between primary forest, secondary forest, primary non-forest, secondary non-forest, cropland, pasture, rangeland, and urban land (Hurtt et al., 2020; Chini et al., 2021). LUH2-GCB2023 provides a distinction between rangelands and pasture, based on inputs from HYDE. To constrain the models’ interpretation on whether rangeland implies the original natural vegetation to be transformed to grassland or not (e.g., browsing on shrubland), a forest mask was provided with LUH2-GCB2021; forest is assumed to be transformed to grasslands, while other natural vegetation remains (in case of secondary vegetation) or is

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degraded from primary to secondary vegetation (Ma et al., 2020). This is implemented in BLUE. OSCAR was run with both LUH2-GCB2023 and FAO/FRA, where the drivers of the latter were linearly extrapolated to 2022 using their 2015-2020 trends. The best-guess OSCAR estimate used in our study is a combination of results for LUH2-GCB2023 and FAO/FRA land-use data and a large number of perturbed parameter simulations weighted against a constraint (the cumulative  $S_{LAND}$  over 1960-2021 of last year's GCB). As the record of H&C2023 ends in 2020, we extend it up to 2022 by adding the yearly anomalies of the emissions from tropical deforestation and degradation, fires from GFED4s between 2020 and 2022 to the model's estimate for 2020 (emissions from peat fires and peat drainage are added to all models later in the process). The annual  $E_{LUC}$  from 1850 onwards is calculated as the average of the estimates from BLUE, H&C2023, and OSCAR. For the cumulative numbers starting in 1750, emission estimates between 1750-1850 are added based on the average of four earlier publications ( $30 \pm 20$  GtC 1750-1850, rounded to nearest 5; Le Quéré et al., 2016).

We provide an additional split of net  $E_{LUC}$  into component fluxes to better identify reasons for divergence between bookkeeping estimates and to give more insight into the drivers of net  $E_{LUC}$ . This split distinguishes between emissions from deforestation (including due to shifting cultivation), removals from forest (re-)growth (including regrowth in shifting cultivation cycles), fluxes from wood harvest and other forest management (i.e., emissions in forests from slash decay and emissions from product decay following wood harvesting, removals from regrowth associated with wood harvesting, and fire suppression), emissions from peat drainage and peat fires, and emissions and removals associated with all other land-use transitions. Additionally, we split deforestation emissions into emissions from permanent deforestation and emissions from deforestation in shifting cultivation cycles, and we split removals from forest (re-)growth into forest (re-)growth due to afforestation and forest regrowth in shifting cultivation cycles. This split helps to identify the emission reductions that would be achievable by halting permanent deforestation, and the removals that are caused by permanently increasing the forest cover through re/afforestation.  $E_{LUC}$  data are provided as global sums, as spatially explicit estimates at  $0.25^\circ$  spatial resolution (i.e., the native BLUE resolution), and for 199 countries (based on the list of UNFCCC parties). Spatially explicit  $E_{LUC}$  estimates for BLUE are directly available. For OSCAR and H&C2023, the country-level estimates were scaled to the  $0.25^\circ$  BLUE grid based on the patterns of gross emissions and gross removals in BLUE (see Schwingshackl et al. 2022 for more details about the methodology). The gridded net  $E_{LUC}$  estimates of BLUE, OSCAR, and H&C2023 are averaged, and the gridded estimates of peat drainage emissions (average of FAO, LPX-Bern, and ORCHIDEE-PEAT) and of peat fire emissions (from GFED4s) are added. Country-level estimates for the gridded datasets (BLUE, LPX-Bern, ORCHIDEE-PEAT, GFED4s) are calculated based on a country map from Eurostat (Countries 2020, 1:1 million, available at: <https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/countries>), which was remapped to  $0.25^\circ$ . In case multiple countries are present in a  $0.25^\circ$  grid cell, the  $E_{LUC}$  estimates are allocated proportional to each country's land fraction in that grid cell.

### C.2.2 Dynamic Global Vegetation Models (DGVMs)

Land-use change  $CO_2$  emissions have also been estimated using an ensemble of 20 DGVMs simulations. The DGVMs account for deforestation and regrowth, the most important components of  $E_{LUC}$ , but they do not represent all processes resulting directly from human activities on land (Table A1). All DGVMs represent

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- Deleted: estimates of the gross land use change fluxes from which the reported net land-use change flux,  $E_{LUC}$ , is derived as a sum. Gross fluxes are derived internally by the three bookkeeping models: Gross emissions stem from decaying material left dead on site and from products after clearing of natural vegetation for agricultural purposes or wood harvesting, emissions from peat drainage and peat burning, and, for BLUE, additionally from degradation from primary to secondary land through usage of natural vegetation as rangeland. Gross removals stem from regrowth after agricultural abandonment and wood harvesting. Gross fluxes for the updated H&N2017 for 2020 and for the 2022 projection of all three models were calculated by th (... [1778])
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processes of vegetation growth and mortality, as well as decomposition of dead organic matter associated with natural cycles, and include the vegetation and soil carbon response to increasing atmospheric CO<sub>2</sub> concentration and to climate variability and change. Most models explicitly simulate the coupling of carbon and nitrogen cycles and account for atmospheric N deposition and N fertilisers (Table A1). The DGVMs are independent from the other budget terms except for their use of atmospheric CO<sub>2</sub> concentration to calculate the fertilisation effect of CO<sub>2</sub> on plant photosynthesis.

All DGVMs use the LUH2-~~GCB2023~~ dataset as input, which includes the HYDE cropland/grazing land dataset (Klein Goldewijk et al., 2017a, 2017b), and ~~some~~ additional information on land-use transitions, ~~land-use management activities~~ and wood harvest. ~~This includes~~ annual, ~~quarter-degree~~ (regridded from 5 minute resolution), fractional data on cropland and pasture from HYDE3.3.

DGVMs that do not simulate subgrid-scale transitions (i.e., net land-use emissions; see Table A1) used the HYDE information on agricultural area change. For all countries, with the exception of Brazil, the Democratic Republic of the Congo, ~~and Indonesia~~ these data are based on the available annual FAO statistics of change in agricultural land area available from 1961 up to and including 2017. The FAO retrospectively revised their reporting for the Democratic Republic of the Congo, which was newly available until 2020, ~~as reported in~~

~~GCB2022~~. In addition to FAO country-level statistics, the HYDE3.3 cropland/grazing land dataset is constrained spatially based on multi-year satellite land cover maps from ESA CCI LC (see below). After the year 2017, ~~HYDE3.3~~ extrapolates the cropland and pasture data based on the trend over the previous 5 years, to generate data until the year 2022. This methodology is not appropriate for countries that have experienced recent rapid changes in the rate of land-use change, e.g. Brazil which has experienced a recent upturn in deforestation. For Brazil ~~and Indonesia~~ we replace FAO state-level data for cropland and grazing land in HYDE by those from the satellite-based land cover dataset MapBiomas (collection 7) for 1985-2021 (Souza et al. 2020). ESA-CCI is used to spatially disaggregate as described below. Similarly, an estimate for the year 2022 is based on the MapBiomas trend 2016-2021. The pre-1985 period is scaled with the per capita numbers from 1985 from MapBiomas, so this transition is smooth.

HYDE uses satellite imagery from ESA-CCI from 1992 – 2018 for more detailed yearly allocation of cropland and grazing land, with the ESA area data scaled to match the FAO annual totals at country-level. The original 300 metre spatial resolution data from ESA was aggregated to a 5 arc minute resolution according to the classification scheme as described in Klein Goldewijk et al (2017a).

DGVMs that simulate subgrid-scale transitions (i.e., gross land-use emissions; see Table A1) use more detailed land use transition and wood harvest information from the LUH2-~~GCB2023~~ data set. LUH2-~~GCB2023~~ is an update of the comprehensive harmonised land-use data set (Hurtt et al., 2020), that includes fractional data on primary and secondary forest vegetation, as well as all underlying transitions between land-use states (850-2020; Hurtt et al., 2011, 2017, 2020; Chini et al., 2021; Table A1). This data set consists of quarter degree fractional areas of land-use states and all transitions between those states, including a new wood harvest reconstruction, new representation of shifting cultivation, crop rotations, management information including irrigation and fertiliser application. The land-use states include five different crop types in addition to splitting grazing land into managed pasture and rangeland. Wood harvest patterns are constrained with Landsat-based tree cover loss data (Hansen et al. 2013). Updates of LUH2-~~GCB2023~~ over last year's version (LUH2-~~GCB2022~~) are using the most recent HYDE release (covering the time period up to 2022, revision to ~~Indonesia~~ as described above). We

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1024 use [updated](#) FAO wood harvest data for all dataset years from 1961 to [2021](#), and [linearly extended](#) to the year  
 1025 [2023](#). The HYDE3.3 population data is also used to extend the wood harvest time series back in time. Other  
 1026 wood harvest inputs (for years prior to 1961) remain the same in LUH2. These updates in the land-use forcing  
 1027 are shown in [Figure B6](#) in comparison to the more pronounced version change from [the GCB2020](#)  
 1028 (Friedlingstein et al., 2020) to GCB2021, which was discussed in Friedlingstein et al. (2022a), and their  
 1029 relevance for land-use emissions [is](#) discussed in Section 3.2.2. DGVMs implement land-use change differently  
 1030 (e.g. an increased cropland fraction in a grid cell can either be at the expense of grassland or shrubs, or forest,  
 1031 the latter resulting in deforestation; land cover fractions of the non-agricultural land differ between models).  
 1032 Similarly, model-specific assumptions are applied to convert deforested biomass or deforested area, and other  
 1033 forest product pools into carbon, and different choices are made regarding the allocation of rangelands as natural  
 1034 vegetation or pastures.

1035 The difference between two DGVMs simulations (see Appendix C4.1 below), one forced with historical  
 1036 changes in land-use and a second [one](#) with time-invariant pre-industrial land cover and pre-industrial wood  
 1037 harvest rates, allows quantification of the dynamic evolution of vegetation biomass and soil carbon pools in  
 1038 response to land-use change in each model (ELUC). Using the difference between these two [DGVM](#) simulations  
 1039 to diagnose ELUC means the [DGVM estimate includes](#) the loss of additional sink capacity (around  $0.4 \pm 0.3$  GtC  
 1040 yr<sup>-1</sup>; see Section 2 [10](#) and Appendix D4), while the bookkeeping [model estimate does not](#).

1041 As a criterion for inclusion in this carbon budget, we only retain models that simulate a positive ELUC during the  
 1042 1990s, as assessed in the IPCC AR4 (Denman et al., 2007) and AR5 (Ciais et al., 2013). [All DGVMs met this](#)  
 1043 [criterion](#).

### 1045 C.2.3 [Translation](#) of national GHG inventory data to ELUC

1046 An approach was implemented to reconcile the large gap between land-use emissions estimates from  
 1047 bookkeeping models and from national GHG Inventories (NGHGI; see Tab. [A9](#)). This gap is due to different  
 1048 approaches [for](#) calculating “anthropogenic” CO<sub>2</sub> fluxes related to land-use change and land management (Grassi  
 1049 et al. 2018). In particular, the land sinks due to environmental change on managed lands are treated as non-  
 1050 anthropogenic in the global carbon budget, while they are generally considered as anthropogenic in NGHGIs  
 1051 (“indirect anthropogenic fluxes”; Eggleston et al., 2006). Building on previous studies (Grassi et al. 2021), the  
 1052 approach implemented here adds the [DGVM](#) estimates of CO<sub>2</sub> fluxes due to environmental change from  
 1053 [managed forest areas](#) (part of SLAND) to the ELUC [estimate from bookkeeping models](#). This sum is expected to be  
 1054 conceptually more comparable to [NGHGI estimates](#) than ELUC.

1055 ELUC data are taken from bookkeeping models, in line with the global carbon budget approach. To determine  
 1056 SLAND [in](#) managed forest, the following steps were taken: Spatially gridded data of “natural” forest NBP (SLAND  
 1057 i.e., [including carbon fluxes](#) due to environmental change and excluding land use change fluxes) were obtained  
 1058 [from DGVMs using](#) S2 runs from [the TRENDY v13](#) dataset. Results were first masked with a forest map that is  
 1059 based on [tree cover data from](#) Hansen et al. (2013). To [perform the conversion](#) “tree” cover to “forest” cover, we  
 1060 exclude gridcells with less than 20% tree cover and isolated pixels with maximum connectivity less than 0.5 ha  
 1061 following the FAO definition of forest. Forest NBP [is](#) then further masked with [a map of](#) “intact” forest for the  
 1062 year 2013, i.e. forest areas characterised by no remotely detected signs of human activity (Potapov et al. 2017).  
 1063 This way, we obtained SLAND in “intact” and “non-intact” forest [areas](#), which previous studies (Grassi et al.

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2021) indicated to be a good proxy, respectively, for “unmanaged” and “managed” forest [areas](#) in the NGHGI. Note that only [a subset of models](#) had forest NBP at grid cell level. For the other DGVMs, when a grid cell had forest, all the NBP [in that grid cell](#) was allocated to forest. However, since S2 simulations use pre-industrial forest cover masks that are at least 20% larger than today’s forest (Hurtt et al. 2020), we corrected this NBP by a ratio between observed (based on Hansen [et al. 2013](#)) and prescribed (from DGVMs) forest cover. This ratio is calculated for each individual DGVM that provides information on prescribed forest cover, [and](#) a common ratio (median ratio of [this subset of models](#)) is used. The details of the method used are explained [in a GitHub repository](#) (Alkama, 2022).

LULUCF data from NGHGIs are from Grassi et al. (2023). While Annex I countries report a complete time series 1990–2021, [gap-filling was applied](#) for Non-Annex I countries through linear interpolation between two points and/or through extrapolation backward (till 1990) and forward (till 2022) using the single closest available data. For all countries, the estimates of the year 2022 are assumed to be equal to those of 2021. This data includes all CO<sub>2</sub> fluxes from land considered managed, which in principle encompasses all land uses (forest land, cropland, grassland, wetlands, settlements, and other land), changes among them, emissions from organic soils ([i.e., from peat drainage](#)) and from fires. In practice, although almost all Annex I countries report all land uses, many non-Annex I countries report only on deforestation and forest land, and only few countries report on other land uses. In most cases, NGHGIs include most of the natural response to recent environmental change, because they use direct observations (e.g., national forest inventories) that do not allow separating direct and indirect anthropogenic effects (Eggleston et al., 2006).

[Tab. A9](#) shows the resulting [translation](#) of global carbon cycle models’ land flux definitions to that of the NGHGI (discussed in Section 3.2.2). [For comparison we also show](#) FAOSTAT emissions totals (FAO, 2021), which include emissions from net forest conversion and fluxes on forest land (Tubiello et al., 2021) as well as CO<sub>2</sub> emissions from peat drainage and peat fires. The 2021 data was estimated by including actual 2021 estimates for [peatland](#) drainage and fire and a carry forward from 2020 to 2021 for the forest land stock change. The FAO data shows global [emissions](#) of 0.25 GtC yr<sup>-1</sup> averaged over 2012–2021, in contrast to the [removals](#) of -0.66 GtC yr<sup>-1</sup> [estimated by the gap-filled](#) NGHGI data. Most of this difference is attributable to different scopes: a focus on carbon fluxes for the NGHGI and a focus on [land-use](#) area and biomass [estimates](#) for FAO. In particular, the NGHGI data includes a larger forest sink for non-Annex 1 countries resulting from a more complete coverage of non-biomass carbon pools and non-forest land uses. NGHGI and FAO data also differ in terms of underlying data on forest land (Grassi et al., 2022).

### C.2.4 Uncertainty assessment for E<sub>LUC</sub>

Differences between the bookkeeping models and DGVMs [originate from three main sources](#): different methodologies, which among others lead to inclusion of the loss of additional sink capacity in DGVMs (see Appendix D1.4), [different underlying land-use/land cover datasets](#), and [different processes represented](#) (Table A1). We examine [both](#) the results from DGVMs [and from](#) the bookkeeping method and use the resulting variations as a way to characterise the uncertainty in E<sub>LUC</sub>.

Despite [the existing](#) differences, the E<sub>LUC</sub> estimate from the [DGVM](#) multi-model mean is consistent with the average of the emissions from the bookkeeping models (Table 5). However there are large differences among individual DGVMs (standard deviation at around 0.5 GtC yr<sup>-1</sup>; Table 5), between the bookkeeping estimates

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(average difference 1850-2022 BLUE-H&C2023 of 0.8 GtC yr<sup>-1</sup>, BLUE-OSCAR of 0.4 GtC yr<sup>-1</sup>, OSCAR-H&C2023 of 0.4 GtC yr<sup>-1</sup>), and between the H&C2023 model and its previous model version H&N2017 (average difference 1850-2015 of 0.2 GtC yr<sup>-1</sup>; see Table 1 in Houghton and Castanho, 2023). A factorial analysis of differences between BLUE and H&N2017 (the precursor of H&C2023) attributed them particularly to differences in carbon densities between natural and managed vegetation or primary and secondary vegetation (Bastos et al., 2021). Earlier studies additionally showed the relevance of the different land-use forcing as applied (in updated versions) also in the current study (Gasser et al., 2020). Ganzenmüller et al. (2022) showed that ELUC estimates with BLUE are substantially smaller when the model is driven by a new high-resolution land-use dataset (HILDA+). They identified shifting cultivation and the way it is implemented in LUH2 as a main reason for this divergence. They further showed that a higher spatial resolution reduces the estimates of both gross emissions and gross removals because successive transitions are not adequately represented at coarser resolution, which has the effect that—despite capturing the same extent of transition areas—overall less area remains pristine at the coarser compared to the higher resolution.

The uncertainty in ELUC of  $\pm 0.7$  GtC yr<sup>-1</sup> reflects our best value judgement that there is at least 68% chance ( $\pm 1\sigma$ ) that the true land-use change emissions lie within the given range, for the range of processes considered here. Prior to the year 1959, the uncertainty in ELUC is taken from the standard deviation of the DGVMs. We assign low confidence to the annual estimates of ELUC because of the inconsistencies among estimates and because of the difficulties to quantify some of the processes with DGVMs.

### C.2.5 Emissions projection for 2023

We project the 2023 land-use emissions for BLUE, H&C2023, and OSCAR based on their ELUC estimates for 2022 and on the interannual variability of peat fires and tropical deforestation and degradation fires as estimated using active fire data (MCD14ML; Giglio et al., 2016). The latter scales almost linearly with GFED emissions estimates over large areas (van der Werf et al., 2017), and thus allows for tracking fire emissions in deforestation and tropical peat zones in near-real time. Peat drainage is assumed to be unaltered, as it has low interannual variability. The 2023 ELUC estimate is calculated by summing the 2022 ELUC estimate and the anomalies in peat fire emissions and tropical deforestation and degradation fire emissions (both from GFED4s), calculated as the difference between the estimates for 2022 and 2023. The GFED4s estimates for 2023 are as of September 29 2023.

## C.3 Methodology Ocean CO<sub>2</sub> sink

### C.3.1 Observation-based estimates

We primarily use the observational constraints assessed by IPCC of a mean ocean CO<sub>2</sub> sink of  $2.2 \pm 0.7$  GtC yr<sup>-1</sup> for the 1990s (90% confidence interval; Ciais et al., 2013) to verify that the GOBMs provide a realistic assessment of SOCEAN. This is based on indirect observations with seven different methodologies and their uncertainties, and further using three of these methods that are deemed most reliable for the assessment of this quantity (Denman et al., 2007; Ciais et al., 2013). The observation-based estimates use the ocean/land CO<sub>2</sub> sink partitioning from observed atmospheric CO<sub>2</sub> and O<sub>2</sub>/N<sub>2</sub> concentration trends (Manning and Keeling, 2006; Keeling and Manning, 2014), an oceanic inversion method constrained by ocean biogeochemistry data (Mikaloff Fletcher et al., 2006), and a method based on penetration time scale for chlorofluorocarbons (McNeil

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et al., 2003). The IPCC estimate of 2.2 GtC yr<sup>-1</sup> for the 1990s is consistent with a range of methods (Wanninkhof et al., 2013). We refrain from using the IPCC estimates for the 2000s ( $2.3 \pm 0.7$  GtC yr<sup>-1</sup>), and the period 2002–2011 ( $2.4 \pm 0.7$  GtC yr<sup>-1</sup>, Ciais et al., 2013) as these are based on trends derived mainly from models and one data-product (Ciais et al., 2013). Additional constraints summarised in AR6 (Canadell et al., 2021) are the interior ocean anthropogenic carbon change (Gruber et al., 2019) and ocean sink estimate from atmospheric CO<sub>2</sub> and O<sub>2</sub>/N<sub>2</sub> (Tohjima et al., 2019) which are used for model evaluation and discussion, respectively.

We also use eight estimates of the ocean CO<sub>2</sub> sink and its variability based on surface ocean *f*CO<sub>2</sub> maps obtained by the interpolation of surface ocean *f*CO<sub>2</sub> measurements from 1990 onwards due to severe restriction in data availability prior to 1990 (Figure 10). These estimates differ in many respects: they use different maps of surface *f*CO<sub>2</sub>, different atmospheric CO<sub>2</sub> concentrations, wind products and different gas-exchange formulations as specified in Table A3. We refer to them as *f*CO<sub>2</sub>-based flux estimates. The measurements underlying the surface *f*CO<sub>2</sub> maps are from the Surface Ocean CO<sub>2</sub> Atlas version 2023 (SOCATv2023; Bakker et al., 2023), which is an update of version 3 (Bakker et al., 2016) and contains quality-controlled data through 2022 (see data attribution Table A6). Each of the estimates uses a different method to then map the SOCAT v2023 data to the global ocean. The methods include a data-driven diagnostic method combined with a multi linear regression approach to extend back to 1957 (Rödenbeck et al., 2022; referred to here as Jena-MLS), three neural network models (Landschützer et al., 2014; referred to as MPI-SOMFFN; Chau et al., 2022; Copernicus Marine Environment Monitoring Service, referred to here as CMEMS-LSCE-FFNN; and Zeng et al., 2022; referred to as NIES-ML3), one cluster regression approaches (Gregor and Gruber, 2021, referred to as OS-ETHZ-GRaCER), and a multi-linear regression method (Iida et al., 2021; referred to as JMA-MLR), and one method that relates the *f*CO<sub>2</sub> misfit between GOBMs and SOCAT to environmental predictors using the extreme gradient boosting method (Gloege et al., 2022). The ensemble mean of the *f*CO<sub>2</sub>-based flux estimates is calculated from these seven mapping methods. Further, we show the flux estimate of Watson et al. (2020) who also use the MPI-SOMFFN method to map the adjusted *f*CO<sub>2</sub> data to the globe, but resulting in a substantially larger ocean sink estimate, owing to a number of adjustments they applied to the surface ocean *f*CO<sub>2</sub> data. Concretely, these authors adjusted the SOCAT *f*CO<sub>2</sub> downward to account for differences in temperature between the depth of the ship intake and the relevant depth right near the surface, and included a further adjustment to account for the cool surface skin temperature effect. The Watson et al. flux estimate hence differs from the others by their choice of adjusting the flux to a cool, salty ocean surface skin. Watson et al. (2020) showed that this temperature adjustment leads to an upward correction of the ocean carbon sink, up to 0.9 GtC yr<sup>-1</sup>, that, if correct, should be applied to all *f*CO<sub>2</sub>-based flux estimates. A reduction of this adjustment to 0.6 GtC yr<sup>-1</sup> was proposed by Dong et al. (2022). The impact of the cool skin effect on air-sea CO<sub>2</sub> flux is based on established understanding of temperature gradients (as discussed by Goddijn-Murphy et al 2015), and laboratory observations (Jähne and Haussecker, 1998; Jähne, 2019), but in situ field observational evidence is lacking (Dong et al., 2022). [A modelling study suggests that the skin effect is important but would be of smaller magnitude \(about 0.1 GtC yr<sup>-1</sup> or 5%\) due to a feedback of larger air-sea flux on ocean surface carbon concentration \(Bellenger et al., 2023\).](#) The Watson et al flux estimate presented here is therefore not included in the ensemble mean of the *f*CO<sub>2</sub>-based flux estimates. This choice will be re-evaluated in upcoming budgets based on further lines of evidence.

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Typically,  $f_{CO_2}$ -products do not cover the entire ocean due to missing coastal oceans and sea ice cover. The  $CO_2$  flux from each  $f_{CO_2}$ -based product is already at or above 99% coverage of the ice-free ocean surface area in two products (Jena-MLS, OS-ETHZ-GRaCER), and filled by the data-provider in three products (using Fay et al., 2021, method for JMA-MLR and LDEO-HPD; and adopting the Landschützer et al., 2020, geographical extension to cover marginal seas and coastal domains for MPI-SOMFFN). The products that did not undergo any area filling from their original published methodology and thus remained below 99% coverage of the ice-free ocean (CMEMS-LSCE-FFNN, NIES-ML3, UOx-Watson) were scaled by the following procedure: Before v2022 of the GCB, the missing areas were accounted for by scaling the globally integrated fluxes by the fraction of the global ocean coverage (361.9e6 km<sup>2</sup> based on ETOPO1, Amante and Eakins, 2009; Eakins and Sharman, 2010) with the area covered by the  $CO_2$  flux predictions. This approach may lead to unnecessary scaling when the majority of the missing data are in the ice-covered region (as is often the case), where flux is already assumed to be zero. Thus, since v2022 of the GCB we now scale fluxes globally and regionally (North, Tropics, South) to match the ice-free area (using the HadISST sea surface temperature and sea ice cover; Rayner et al., 2003):

$$FCO_2^{reg-scaled} = \frac{A_{region}^{(1-ice)}}{A_{FCO_2}^{region}} \cdot FCO_2^{region}$$

In the equation,  $A$  represents area,  $(1 - ice)$  represents the ice free ocean,  $A_{FCO_2}^{region}$  represents the coverage of the  $f_{CO_2}$ -product for a region, and  $FCO_2^{region}$  is the integrated flux for a region. We further use results from two diagnostic ocean models, Khatiwala et al. (2013) and DeVries (2014), to estimate the anthropogenic carbon accumulated in the ocean prior to 1959. The two approaches assume constant ocean circulation and biological fluxes, with  $SO_{OCEAN}$  estimated as a response in the change in atmospheric  $CO_2$  concentration calibrated to observations. The uncertainty in cumulative uptake of  $\pm 20$  GtC (converted to  $\pm 1\sigma$ ) is taken directly from the IPCC's review of the literature (Rhein et al., 2013), or about  $\pm 30\%$  for the annual values (Khatiwala et al., 2009).

### C.3.2 Global Ocean Biogeochemistry Models (GOBMs)

The ocean  $CO_2$  sink for 1959-2022 is estimated using ten GOBMs (Table A2). The GOBMs represent the physical, chemical, and biological processes that influence the surface ocean concentration of  $CO_2$  and thus the air-sea  $CO_2$  flux. The GOBMs are forced by meteorological reanalysis and atmospheric  $CO_2$  concentration data available for the entire time period. They mostly differ in the source of the atmospheric forcing data (meteorological reanalysis), spin up strategies, and in their horizontal and vertical resolutions (Table A2). All GOBMs except one (CESM-ETHZ) do not include the effects of anthropogenic changes in nutrient supply (Duce et al., 2008). They also do not include the perturbation associated with changes in riverine organic carbon (see Section 2.10 and Appendix D.3).

Four sets of simulations were performed with each of the GOBMs. Simulation A applied historical changes in climate and atmospheric  $CO_2$  concentration. Simulation B is a control simulation with constant atmospheric forcing (normal year or repeated year forcing) and constant pre-industrial atmospheric  $CO_2$  concentration. Simulation C is forced with historical changes in atmospheric  $CO_2$  concentration, but repeated year or normal year atmospheric climate forcing. Simulation D is forced by historical changes in climate and constant pre-industrial atmospheric  $CO_2$  concentration. To derive  $SO_{OCEAN}$  from the model simulations, we subtracted the slope

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of a linear fit to the annual time series of the control simulation B from the annual time series of simulation A. Assuming that drift and bias are the same in simulations A and B, we thereby correct for any model drift. Further, this difference also removes the natural steady state flux (assumed to be 0 GtC yr<sup>-1</sup> globally without rivers) which is often a major source of biases. [Note, however, that Gürses et al. \(2023\) questioned the assumption of comparable bias and drift in simulations A and B as they compared two versions of FESOM-REcoM, and found a very similar air-sea CO<sub>2</sub> flux in simulation A despite a different bias as derived from simulation B.](#) This approach works for all model set-ups, including IPSL, where simulation B was forced with constant atmospheric CO<sub>2</sub> but observed historical changes in climate (equivalent to simulation D). This approach assures that the interannual variability is not removed from IPSL simulation A. The absolute correction for bias and drift per model in the 1990s varied between <0.01 GtC yr<sup>-1</sup> and 0.31 GtC yr<sup>-1</sup>, with [five](#) models having positive biases, [four](#) having negative biases and one model having essentially no bias (NorESM). The MPI model uses riverine input and therefore simulates outgassing in simulation B. By subtracting [a linear fit of](#) simulation B, also the ocean carbon sink of the MPI model follows the definition of Socean. This correction reduces the model mean ocean carbon sink by 0.01 GtC yr<sup>-1</sup> in the 1990s. The ocean models cover 99% to 101% of the total ocean area, so that area-scaling is not necessary.

### C.3.3 GOBM evaluation

The ocean CO<sub>2</sub> sink for all GOBMs and the ensemble mean falls within 90% confidence of the observed range, or 1.5 to 2.9 GtC yr<sup>-1</sup> for the 1990s (Ciais et al., 2013) before and after applying adjustments. An exception is the MPI model, which simulates a low ocean carbon sink of 1.38 GtC yr<sup>-1</sup> for the 1990s in simulation A owing to the inclusion of riverine carbon flux. After adjusting to the GCB's definition of Socean by subtracting simulation B, the MPI model falls into the observed range with an estimated sink of 1.69 GtC yr<sup>-1</sup>.

The GOBMs and [fCO<sub>2</sub>](#)-products have been further evaluated using the fugacity of sea surface CO<sub>2</sub> ([fCO<sub>2</sub>](#)) from the SOCAT [v2023](#) database (Bakker et al., 2016, [2023](#)). We focused this evaluation on the root mean squared error (RMSE) between observed and modelled [fCO<sub>2</sub>](#) and on a measure of the amplitude of the interannual variability of the flux (modified after Rödenbeck et al., 2015). [The RMSE is calculated from detrended, annually and regionally averaged time series of fCO<sub>2</sub> calculated from GOBMs and fCO<sub>2</sub>-products subsampled to SOCAT sampling points to measure the misfit between large-scale signals \(Hauck et al., 2020\). To this end, we apply the following steps: \(i\) subsample data points for where there are observations \(GOBMs/fCO<sub>2</sub>-products as well as SOCAT\), \(ii\) average spatially, \(iii\) calculate annual mean, \(iv\) detrend both time-series \(GOBMs/fCO<sub>2</sub>-products as well as SOCAT\), \(v\) calculate RMSE. We use a mask based on the minimum area coverage of the fCO<sub>2</sub>-products. This ensures a fair comparison over equal areas. The amplitude of the Socean interannual variability \(A-IAV\) is calculated as the temporal standard deviation of the detrended annual CO<sub>2</sub> flux time series after area-scaling \(Rödenbeck et al., 2015, Hauck et al., 2020\). These metrics are chosen because RMSE is the most direct measure of data-model mismatch and the A-IAV is a direct measure of the variability of Socean on interannual timescales. We apply these metrics globally and by latitude bands. Results are shown in Figure B2 and discussed in Section 3.6.5.](#)

[In addition to the interior ocean anthropogenic carbon accumulation \(Section 3.6.5\) and SOCAT /CO<sub>2</sub>, we evaluate the models with process-based metrics that were previously related to ocean carbon uptake. These are](#)

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the Atlantic Meridional Overturning Circulation (Goris et al., 2018, Terhaar et al., 2022, Terhaar et al., in review), the Southern Ocean sea surface salinity (Terhaar et al., 2021, 2022, in review, Hauck et al., in review), the Southern Ocean stratification index (Bourgeois et al., 2022) and the surface ocean Revelle factor (Terhaar et al., 2022, in review).

We follow the methodology of previous studies wherever possible, particularly the RECCAP model evaluation chapter (Terhaar et al., in review). The Atlantic Meridional Overturning Circulation from the GOBMs is here defined as the maximum of the Atlantic meridional overturning streamfunction at 26°N. This is compared to data from the RAPID array at 26°N (Moat et al., 2023). We use an uncertainty of 0.6 Sv following Terhaar et al. (in review) based on reported uncertainties in McCarthy et al. (2015). We use the years 2005-2021, which are all complete calendar years available from the RAPID data set.

The Southern Ocean sea surface salinity is reported for the subpolar seasonally stratified biome (SPSS, averaged on the native model mesh by the model providers) and for the area covering both the SPSS and STSS (subtropical seasonally stratified biome) biomes with the latter being calculated from 1°x1° gridded model sea surface salinity fields. Biome definitions are taken from Fay and McKinley (2014, as provided for the RECCAP project). The averages over the SPSS biome were checked for consistency with the gridded fields. The sea surface salinity was first used as an emergent constraint for the Southern Ocean CO<sub>2</sub> uptake by Earth System Models (Terhaar et al. 2021, 2022) using the interfrontal salinity between the polar and subtropical fronts with dynamic fronts. As the GOBMs are forced with reanalysis data, the fronts do not vary as much as in the ESMs, and thus the use of fixed biomes is justified (Hauck et al., in review, Terhaar et al., in review). We use the time period 2005-2021 for consistency with the AMOC metric. The observational sea surface salinity values are calculated from the EN4 data set (Good et al., 2013; using the objective analyses – Gouretski and Reseghetti (2010) XBT corrections and Gouretski and Cheng (2020) MBT corrections) with the aid of the Fay and McKinley (2014) mask.

The Southern Ocean stratification index is a simplified version of the metric used in Bourgeois et al. (2022). It is defined as the difference between in situ density at the surface and at 1000 m depth in the latitudinal band of 30°S to 55°S. Each model provider calculated this metric based on their native model mesh. We use again the period of 2005-2021 for consistency with the AMOC metric. The same metric was calculated from the EN4 data set mentioned above (Good et al., 2013).

Finally, the global surface ocean Revelle factor is reported. Monthly 1°x1° gridded fields were provided by the modelling groups, based on standard carbonate chemistry routines (e.g., mocsy, Orr & Epitalon, 2015; PyCO2SYS, Humphreys et al., 2022a,b). The observational metrics come from two sources, firstly the gridded GLODAP data set v2.2016 (Lauvset et al., 2016), which is a climatology centered around the year 2002. For comparison with GLODAP, the models were subsampled to GLODAP data coverage and to a comparable time window also centred around 2002 (1997-2007). Secondly, the OceanSODA v2023 data set (Gregor and Gruber, 2020, updated) was used, which has all input data available to calculate the surface ocean Revelle factor. OceanSODA covers a slightly smaller surface area (~96 % of GLODAP), but provides data until 2022. Again,

1479 for consistency with the other metrics, the period 2005-2021 was used and the models were subsampled to the  
1480 same spatial and temporal coverage..

1481  
1482 For this release, only the comparison of the metrics between GOBMs and observational data sets is presented,  
1483 whereas it is foreseen to translate this comparison into a quantitative benchmarking comparable to the iLAMB  
1484 benchmarking for the DGVMs and the corresponding iOMB framework (Ogunro et al., 2018). In a next step,  
1485 model weighting can be applied based on the benchmarking (e.g., Brunner et al., 2020).

### 1487 C3.4 Uncertainty assessment for Socean

1488 We quantify the 1- $\sigma$  uncertainty around the mean ocean sink of anthropogenic CO<sub>2</sub> by assessing random and  
1489 systematic uncertainties for the GOBMs and  $f$ CO<sub>2</sub>-products. The random uncertainties are taken from the  
1490 ensemble standard deviation (0.3 GtC yr<sup>-1</sup> for GOBMs, 0.3 GtC yr<sup>-1</sup> for  $f$ CO<sub>2</sub>-products). We derive the GOBMs  
1491 systematic uncertainty by the deviation of the DIC inventory change 1994-2007 from the Gruber et al (2019)  
1492 estimate (0.4 GtC yr<sup>-1</sup>) and suggest these are related to physical transport (mixing, advection) into the ocean  
1493 interior. For the  $f$ CO<sub>2</sub>-products, we consider systematic uncertainties stemming from uncertainty in  $f$ CO<sub>2</sub>  
1494 observations (0.2 GtC yr<sup>-1</sup>, Takahashi et al., 2009; Wanninkhof et al., 2013), gas-transfer velocity (0.2 GtC yr<sup>-1</sup>,  
1495 Ho et al., 2011; Wanninkhof et al., 2013; Roobaert et al., 2018), wind product (0.1 GtC yr<sup>-1</sup>, Fay et al., 2021),  
1496 river flux adjustment (0.3 GtC yr<sup>-1</sup>, Regnier et al., 2022, formally 2- $\sigma$  uncertainty), and  $f$ CO<sub>2</sub> mapping (0.2 GtC  
1497 yr<sup>-1</sup>, Landschützer et al., 2014). Combining these uncertainties as their squared sums, we assign an uncertainty  
1498 of  $\pm 0.5$  GtC yr<sup>-1</sup> to the GOBMs ensemble mean and an uncertainty of  $\pm 0.6$  GtC yr<sup>-1</sup> to the  $f$ CO<sub>2</sub>-product  
1499 ensemble mean. These uncertainties are propagated as  $\sigma(\text{Socean}) = (1/2^2 * 0.5^2 + 1/2^2 * 0.6^2)^{1/2}$  GtC yr<sup>-1</sup> and  
1500 result in an  $\pm 0.4$  GtC yr<sup>-1</sup> uncertainty around the best estimate of Socean.

1501  
1502 We examine the consistency between the variability of the GOBMs and the  $f$ CO<sub>2</sub>-products to assess confidence  
1503 in Socean. The interannual variability of the ocean fluxes (quantified as A-IAV, the standard deviation after  
1504 detrending, Figure B2) of the seven  $f$ CO<sub>2</sub>-products plus the Watson et al. (2020) product for 1990-2022, ranges  
1505 from 0.10 to 0.31 GtC yr<sup>-1</sup> with the lower estimates by the three ensemble methods (NIES-ML3, CMEMS-  
1506 LSCE-FFNN, OS-ETHZ-GRaCER). The inter-annual variability in the GOBMs ranges between 0.11 and 0.20  
1507 GtC yr<sup>-1</sup>, hence there is overlap with the lower A-IAV estimates of three  $f$ CO<sub>2</sub>-products.

1508  
1509 Individual estimates (both GOBMs and  $f$ CO<sub>2</sub>products) generally produce a higher ocean CO<sub>2</sub> sink during strong  
1510 El Niño events. There is emerging agreement between GOBMs and  $f$ CO<sub>2</sub>-products on the patterns of decadal  
1511 variability of Socean with a global stagnation in the 1990s and an extra-tropical strengthening in the 2000s  
1512 (McKinley et al., 2020, Hauck et al., 2020) and also on the stagnation or decline of Socean in the triple La Niña  
1513 years 2020-2023. The central estimates of the annual flux from the GOBMs and the  $f$ CO<sub>2</sub>-products have a  
1514 correlation  $r$  of 0.96 (1990-2022). The agreement between the models and the  $f$ CO<sub>2</sub>products reflects some  
1515 consistency in their representation of underlying variability since there is little overlap in their methodology or  
1516 use of observations.

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## 1542 C.4 Methodology Land CO<sub>2</sub> sink

### 1543 C.4.1 DGVM simulations

1544 The DGVMs model runs were forced by either the merged monthly Climate Research Unit (CRU) and 6 hourly  
1545 Japanese 55-year Reanalysis (JRA-55) data set or by the monthly CRU data set, both providing observation-  
1546 based temperature, precipitation, and incoming surface radiation on a 0.5°x0.5° grid and updated to 2021 (Harris  
1547 et al., 2014, 2020). The combination of CRU monthly data with 6 hourly forcing from JRA-55 (Kobayashi et al.,  
1548 2015) is performed with methodology used in previous years (Viovy, 2016) adapted to the specifics of the JRA-  
1549 55 data.

1550 Introduced in GCB2021 (Friedlingstein et al., 2022a), incoming short-wave radiation fields take into account  
1551 aerosol impacts and the division of total radiation into direct and diffuse components as summarised below.

1552 The diffuse fraction dataset offers 6-hourly distributions of the diffuse fraction of surface shortwave fluxes over  
1553 the period 1901-2022. Radiative transfer calculations are based on monthly-averaged distributions of  
1554 tropospheric and stratospheric aerosol optical depth, and 6-hourly distributions of cloud fraction. Methods  
1555 follow those described in the Methods section of Mercado et al. (2009), but with updated input datasets.

1556 The time series of speciated tropospheric aerosol optical depth is taken from the historical and RCP8.5  
1557 simulations by the HadGEM2-ES climate model (Bellouin et al., 2011). To correct for biases in HadGEM2-ES,  
1558 tropospheric aerosol optical depths are scaled over the whole period to match the global and monthly averages  
1559 obtained over the period 2003-2020 by the CAMS Reanalysis of atmospheric composition (Inness et al., 2019),  
1560 which assimilates satellite retrievals of aerosol optical depth.

1561 The time series of stratospheric aerosol optical depth is taken from the by Sato et al. (1993) climatology, which  
1562 has been updated to 2012. Years 2013-2020 are assumed to be background years so replicate the background  
1563 year 2010. That assumption is supported by the Global Space-based Stratospheric Aerosol Climatology time  
1564 series (1979-2016; Thomason et al., 2018). The time series of cloud fraction is obtained by scaling the 6-hourly  
1565 distributions simulated in the Japanese Reanalysis (Kobayashi et al., 2015) to match the monthly-averaged cloud  
1566 cover in the CRU TS v4.06 dataset (Harris et al., 2020). Surface radiative fluxes account for aerosol-radiation  
1567 interactions from both tropospheric and stratospheric aerosols, and for aerosol-cloud interactions from  
1568 tropospheric aerosols, except mineral dust. Tropospheric aerosols are also assumed to exert interactions with  
1569 clouds.

1570 The radiative effects of those aerosol-cloud interactions are assumed to scale with the radiative effects of  
1571 aerosol-radiation interactions of tropospheric aerosols, using regional scaling factors derived from HadGEM2-  
1572 ES. Diffuse fraction is assumed to be 1 in cloudy sky. Atmospheric constituents other than aerosols and clouds  
1573 are set to a constant standard mid-latitude summer atmosphere, but their variations do not affect the diffuse  
1574 fraction of surface shortwave fluxes.

1575 In summary, the DGVMs forcing data include time dependent gridded climate forcing, global atmospheric CO<sub>2</sub>  
1576 (Lan et al. (2023)), gridded land cover changes (see Appendix C.2.2), and gridded nitrogen deposition and  
1577 fertilisers (see Table A1 for specific models details).

1578 Four simulations were performed with each of the DGVMs. Simulation 0 (S0) is a control simulation which  
1579 uses fixed pre-industrial (year 1700) atmospheric CO<sub>2</sub> concentrations, cycles early 20th century (1901-1920)  
1580 climate and applies a time-invariant pre-industrial land cover distribution and pre-industrial wood harvest rates.  
1581 Simulation 1 (S1) differs from S0 by applying historical changes in atmospheric CO<sub>2</sub> concentration and N

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1585 inputs. Simulation 2 (S2) applies historical changes in atmospheric CO<sub>2</sub> concentration, N inputs, and climate,  
1586 while applying time-invariant pre-industrial land cover distribution and pre-industrial wood harvest rates.  
1587 Simulation 3 (S3) applies historical changes in atmospheric CO<sub>2</sub> concentration, N inputs, climate, and land  
1588 cover distribution and wood harvest rates.  
1589 S2 is used to estimate the land sink component of the global carbon budget (S<sub>LAND</sub>). S3 is used to estimate the  
1590 total land flux but is not used in the global carbon budget. We further separate S<sub>LAND</sub> into contributions from  
1591 CO<sub>2</sub> (=S1-S0) and climate (=S2-S1+S0).

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#### 1593 C.4.2 DGVM evaluation and uncertainty assessment for S<sub>LAND</sub> and net land flux

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1594 We apply three criteria for minimum DGVMs realism by including only those DGVMs with (1) steady state  
1595 after spin up, (2) global net land flux (S<sub>LAND</sub> – E<sub>LUC</sub>) that is an atmosphere-to-land carbon flux over the 1990s  
1596 ranging between -0.3 and 2.3 GtC yr<sup>-1</sup>, within 90% confidence of constraints by global atmospheric and oceanic  
1597 observations (Keeling and Manning, 2014; Wanninkhof et al., 2013), and (3) global E<sub>LUC</sub> that is a carbon source  
1598 to the atmosphere over the 1990s, as already mentioned in Appendix C.2.2. All DGVMs meet these three  
1599 criteria.

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1600 In addition, the DGVMs results are also evaluated using the International Land Model Benchmarking system  
1601 (ILAMB; Collier et al., 2018). This evaluation is provided here to document, encourage and support model  
1602 improvements through time. ILAMB variables cover key processes that are relevant for the quantification of  
1603 S<sub>LAND</sub> and resulting aggregated outcomes. The selected variables are vegetation biomass, gross primary  
1604 productivity, leaf area index, net ecosystem exchange, ecosystem respiration, evapotranspiration, soil carbon,  
1605 runoff, and relationships between carbon cycle variables, precipitation (Adler et al., 2003) and temperature  
1606 (Harris et al., 2014) (see Figure B3 for the results and for the list of observed databases). Results are shown in  
1607 Figure B3 and briefly discussed in Section 3.7.5.

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1608 For the uncertainty for S<sub>LAND</sub>, we use the standard deviation of the annual CO<sub>2</sub> sink across the DGVMs,  
1609 averaging to about ± 0.6 GtC yr<sup>-1</sup> for the period 1959 to 2021. We attach a medium confidence level to the  
1610 annual land CO<sub>2</sub> sink and its uncertainty because the estimates from the residual budget and averaged DGVMs  
1611 match well within their respective uncertainties (Table 5).

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### 1613 C.5 Methodology Atmospheric Inversions

#### 1614 C.5.1 Inversion System Simulations

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1615 Fourteen atmospheric inversions (details of each in Table A4) were used to infer the spatio-temporal distribution  
1616 of the CO<sub>2</sub> flux exchanged between the atmosphere and the land or oceans. These inversions are based on  
1617 Bayesian inversion principles with prior information on fluxes and their uncertainties. They use very similar sets  
1618 of surface measurements of CO<sub>2</sub> time series (or subsets thereof) from various flask and in situ networks. Six  
1619 inversion systems used satellite xCO<sub>2</sub> retrievals from GOSAT and OCO-2, of which two systems used a  
1620 combination of satellite and surface observations.

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1621 Each inversion system uses different methodologies and input data but is rooted in Bayesian inversion  
1622 principles. These differences mainly concern the selection of atmospheric CO<sub>2</sub> data and prior fluxes, as well as  
1623 the spatial resolution, assumed correlation structures, and mathematical approach of the models. Each system  
1624 uses a different transport model, which was demonstrated to be a driving factor behind differences in

atmospheric inversion-based flux estimates, and specifically their distribution across latitudinal bands (Gaubert et al., 2019; Schuh et al., 2019).

Most of the fourteen inversion systems prescribe similar global fossil fuel emissions for  $E_{FOS}$ ; specifically, the GCP's Gridded Fossil Emissions Dataset version 2023.1 (GCP-GridFEDv2023.1; Jones et al., 2023), which is an update through 2022 of the first version of GCP-GridFED presented by Jones et al. (2021b) (Table A4). All GCP-GridFED versions scale gridded estimates of CO<sub>2</sub> emissions from EDGARv4.3.2 (Janssens-Maenhout et al., 2019) within national territories to match national emissions estimates provided by the GCP for the years 1959–2022, which are compiled following the methodology described in Appendix C.1. GCP-GridFEDv2023.1 adopts the seasonality of emissions (the monthly distribution of annual emissions) from the Carbon Monitor (Liu et al., 2020a,b; Dou et al., 2022) for Brazil, China, all EU27 countries, the United Kingdom, the USA and shipping and aviation bunker emissions. The seasonality present in Carbon Monitor is used directly for years 2019–2022, while for years 1959–2018 the average seasonality of 2019, and 2021 and 2022 are applied (avoiding the year 2020 during which emissions were most impacted by the COVID-19 pandemic). For all other countries, seasonality of emissions is taken from EDGAR (Janssens-Maenhout et al., 2019; Jones et al., 2023), with small annual correction to the seasonality present in 2010 based on heating or cooling degree days to account for the effects of inter-annual climate variability on the seasonality of emissions (Jones et al., 2021b). Small remaining differences between regriding of the GridFED inputs, or the use of different fossil fuel emission priors are corrected for by scaling the resulting inverse fluxes to GridFEDv2023.1. The consistent use of  $E_{FOS}$  ensures a close alignment with the estimate of  $E_{FOS}$  used in this budget assessment, enhancing the comparability of the inversion-based estimate with the flux estimates deriving from DGVMs, GOBMs and fCO<sub>2</sub>-based methods. The fossil fuel adjustment (including emissions from cement production and cement carbonation CO<sub>2</sub> sink) ensures that the estimated uptake of atmospheric CO<sub>2</sub> by the land and oceans was fully consistent within the inversion ensemble.

The land and ocean CO<sub>2</sub> fluxes from atmospheric inversions contain anthropogenic perturbation and natural pre-industrial CO<sub>2</sub> fluxes. On annual time scales, natural pre-industrial fluxes are primarily land CO<sub>2</sub> sinks and ocean CO<sub>2</sub> sources corresponding to carbon taken up on land, transported by rivers from land to ocean, and outgassed by the ocean. These pre-industrial land CO<sub>2</sub> sinks are thus compensated over the globe by ocean CO<sub>2</sub> sources corresponding to the outgassing of riverine carbon inputs to the ocean, using the exact same numbers and distribution as described for the oceans in Section 2.5. To facilitate the comparison, we adjusted the inverse estimates of the land and ocean fluxes per latitude band with these numbers to produce historical perturbation CO<sub>2</sub> fluxes from inversions.

### C.5.2 Inversion System Evaluation

All participating atmospheric inversions are checked for consistency with the annual global growth rate, as both are derived from the global surface network of atmospheric CO<sub>2</sub> observations. In this exercise, we use the conversion factor of 2.086 GtC/ppm to convert the inverted carbon fluxes to mole fractions, as suggested by Prather (2012). This number is specifically suited for the comparison to surface observations that do not respond uniformly, nor immediately, to each year's summed sources and sinks. This factor is therefore slightly smaller than the GCB conversion factor in Table 1 (2.142 GtC/ppm, Ballantyne et al., 2012). Overall, the inversions

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Deleted: (2021). Earlier versions of GridFED used Carbon Monitor-based seasonality only during the years 2019 onwards. In addition, we note that GCP-GridFEDv2022.1 and v2022.2 include emissions from cement production and the cement carbonation CO<sub>2</sub> sink (Appendix C.1.1), whereas earlier versions of GCP-GridFED did not include the cement carbonation CO<sub>2</sub> sink.

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1699 agree with the growth rate with biases between 0.002-0.041 ppm yr<sup>-1</sup> (0.005-0.09 GtCyr<sup>-1</sup>) for the period 2015-  
 1700 2022, except for MIROC4-ACTM, which has a larger bias at 0.09 ppm yr<sup>-1</sup>.  
 1701 The atmospheric inversions are also evaluated using vertical profiles of atmospheric CO<sub>2</sub> concentrations (Figure  
 1702 B4). More than 30 aircraft programs over the globe, either regular programs or repeated surveys over at least 9  
 1703 months (except on the SH), have been used in order to draw a robust picture of the system performance (with  
 1704 space-time data coverage irregular and denser in the 0-45°N latitude band; Table A6 and lower panel in Figure  
 1705 B4). The fourteen systems are compared to these independent aircraft CO<sub>2</sub> observations between 2 and 7 km  
 1706 above sea level between 2001 and 2022. Results are shown in Figure B4, where the inversions generally match  
 1707 the atmospheric mole fractions to within 0.7 ppm at all latitudes, except for MIROC4-ACTM in the Northern  
 1708 Hemisphere in the 2015-2022 period. Based on this larger bias with also larger standard deviations, plus the  
 1709 larger bias for the growth rate, the results for MIROC4-ACTM are not included in the statistics of the inversion  
 1710 ensemble.

1711 **Appendix D: Processes not included in the global carbon budget**

1712 **D.1 Contribution of anthropogenic CO and CH<sub>4</sub> to the global carbon budget**

1713 Equation (1) includes only partly the net input of CO<sub>2</sub> to the atmosphere from the chemical oxidation of reactive  
 1714 carbon-containing gases from sources other than the combustion of fossil fuels, such as: (1) cement process  
 1715 emissions, since these do not come from combustion of fossil fuels, (2) the oxidation of fossil fuels, (3) the  
 1716 assumption of immediate oxidation of vented methane in oil production. However, it omits any other  
 1717 anthropogenic carbon-containing gases that are eventually oxidised in the atmosphere, forming a diffuse source  
 1718 of CO<sub>2</sub>, such as anthropogenic emissions of CO and CH<sub>4</sub>. An attempt is made in this section to estimate their  
 1719 magnitude and identify the sources of uncertainty. Anthropogenic CO emissions are from incomplete fossil fuel  
 1720 and biofuel burning and deforestation fires. The main anthropogenic emissions of fossil CH<sub>4</sub> that matter for the  
 1721 global (anthropogenic) carbon budget are the fugitive emissions of coal, oil and gas sectors (see below). These  
 1722 emissions of CO and CH<sub>4</sub> contribute a net addition of fossil carbon to the atmosphere.

1723 In our estimate of E<sub>FOS</sub> we assumed (Section 2.1.1) that all the fuel burned is emitted as CO<sub>2</sub>, thus CO  
 1724 anthropogenic emissions associated with incomplete fossil fuel combustion and its atmospheric oxidation into  
 1725 CO<sub>2</sub> within a few months are already counted implicitly in E<sub>FOS</sub> and should not be counted twice (same for E<sub>LUC</sub>  
 1726 and anthropogenic CO emissions by deforestation fires). The diffuse atmospheric source of CO<sub>2</sub> deriving from  
 1727 anthropogenic emissions of fossil CH<sub>4</sub> is not included in E<sub>FOS</sub>. In reality, the diffuse source of CO<sub>2</sub> from CH<sub>4</sub>  
 1728 oxidation contributes to the annual CO<sub>2</sub> growth. Emissions of fossil CH<sub>4</sub> represent 30% of total anthropogenic  
 1729 CH<sub>4</sub> emissions (Saunois et al. 2020; their top-down estimate is used because it is consistent with the observed  
 1730 CH<sub>4</sub> growth rate), that is 0.083 GtC yr<sup>-1</sup> for the decade 2008-2017. Assuming steady state, an amount equal to  
 1731 this fossil CH<sub>4</sub> emission is all converted to CO<sub>2</sub> by OH oxidation, and thus explain 0.083 GtC yr<sup>-1</sup> of the global  
 1732 CO<sub>2</sub> growth rate with an uncertainty range of 0.061 to 0.098 GtC yr<sup>-1</sup> taken from the min-max of top-down  
 1733 estimates in Saunois et al. (2020). If this min-max range is assumed to be 2 σ because Saunois et al. (2020) did  
 1734 not account for the internal uncertainty of their min and max top-down estimates, it translates into a 1-σ  
 1735 uncertainty of 0.019 GtC yr<sup>-1</sup>.

1736 Other anthropogenic changes in the sources of CO and CH<sub>4</sub> from wildfires, vegetation biomass, wetlands,  
 1737 ruminants, or permafrost changes are similarly assumed to have a small effect on the CO<sub>2</sub> growth rate. The CH<sub>4</sub>

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1754 and CO emissions and sinks are published and analysed separately in the Global Methane Budget and Global  
1755 Carbon Monoxide Budget publications, which follow a similar approach to that presented here (Saunio et al.,  
1756 2020; Zheng et al., 2019).

1757  
1758 **D.2 Contribution of other carbonates to CO<sub>2</sub> emissions**

1759 Although we do account for cement carbonation (a carbon sink), the contribution of emissions of fossil  
1760 carbonates (carbon sources) other than cement production is not systematically included in estimates of E<sub>FOS</sub>,  
1761 except for Annex I countries and lime production in China (Andrew and Peters, 2021). The missing processes  
1762 include CO<sub>2</sub> emissions associated with the calcination of lime and limestone outside of cement production.  
1763 Carbonates are also used in various industries, including in iron and steel manufacture and in agriculture. They  
1764 are found naturally in some coals. CO<sub>2</sub> emissions from fossil carbonates other than cement not included in our  
1765 dataset are estimated to amount to about 0.3% of E<sub>FOS</sub> (estimated based on Crippa et al., 2019).

1766  
1767 **D.3 Anthropogenic carbon fluxes in the land-to-ocean aquatic continuum**

1768 The approach used to determine the global carbon budget refers to the mean, variations, and trends in the  
1769 perturbation of CO<sub>2</sub> in the atmosphere, referenced to the pre-industrial era. Carbon is continuously displaced  
1770 from the land to the ocean through the land-ocean aquatic continuum (LOAC) comprising freshwaters, estuaries,  
1771 and coastal areas (Bauer et al., 2013; Regnier et al., 2013). A substantial fraction of this lateral carbon flux is  
1772 entirely ‘natural’ and is thus a steady state component of the pre-industrial carbon cycle. We account for this  
1773 pre-industrial flux where appropriate in our study (see Appendix C.3). However, changes in environmental  
1774 conditions and land-use change have caused an increase in the lateral transport of carbon into the LOAC – a  
1775 perturbation that is relevant for the global carbon budget presented here.

1776 The results of the analysis of Regnier et al. (2013) can be summarised in two points of relevance for the  
1777 anthropogenic CO<sub>2</sub> budget. First, the anthropogenic perturbation of the LOAC has increased the organic carbon  
1778 export from terrestrial ecosystems to the hydrosphere by as much as  $1.0 \pm 0.5 \text{ GtC yr}^{-1}$  since pre-industrial  
1779 times, mainly owing to enhanced carbon export from soils. Second, this exported anthropogenic carbon is partly  
1780 respired through the LOAC, partly sequestered in sediments along the LOAC and to a lesser extent, transferred  
1781 to the open ocean where it may accumulate or be outgassed. The increase in storage of land-derived organic  
1782 carbon in the LOAC carbon reservoirs (burial) and in the open ocean combined is estimated by Regnier et al.  
1783 (2013) at  $0.65 \pm 0.35 \text{ GtC yr}^{-1}$ . The inclusion of LOAC related anthropogenic CO<sub>2</sub> fluxes should affect estimates  
1784 of S<sub>LAND</sub> and S<sub>OCEAN</sub> in Eq. (1) but does not affect the other terms. Representation of the anthropogenic  
1785 perturbation of LOAC CO<sub>2</sub> fluxes is however not included in the GOBMs and DGVMs used in our global  
1786 carbon budget analysis presented here.

1787  
1788 **D.4 Loss of additional land sink capacity**

1789 Historical land-cover change was dominated by transitions from vegetation types that can provide a large carbon  
1790 sink per area unit (typically, forests) to others less efficient in removing CO<sub>2</sub> from the atmosphere (typically,  
1791 croplands). The resultant decrease in land sink, called the ‘loss of additional sink capacity’, can be calculated as  
1792 the difference between the actual land sink under changing land-cover and the counterfactual land sink under  
1793 pre-industrial land-cover. This term is not accounted for in our global carbon budget estimate. Here, we provide

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1794 a quantitative estimate of this term to be used in the discussion. Seven of the DGVMs used in Friedlingstein et  
1795 al. (2019) performed additional simulations with and without land-use change under cycled pre-industrial  
1796 environmental conditions. The resulting loss of additional sink capacity amounts to  $0.9 \pm 0.3 \text{ GtC yr}^{-1}$  on  
1797 average over 2009-2018 and  $42 \pm 16 \text{ GtC}$  accumulated between 1850 and 2018 (Obermeier et al., 2021).  
1798 OSCAR, emulating the behaviour of 11 DGVMs finds values of the loss of additional sink capacity of  $0.7 \pm 0.6$   
1799  $\text{GtC yr}^{-1}$  and  $31 \pm 23 \text{ GtC}$  for the same time period (Gasser et al., 2020). Since the DGVM-based ELUC  
1800 estimates are only used to quantify the uncertainty around the bookkeeping models' ELUC, we do not add the  
1801 loss of additional sink capacity to the bookkeeping estimate.

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Table A4. Comparison of the inversion set up and input fields for the atmospheric inversions. Atmospheric inversions see the full CO<sub>2</sub> fluxes, including the anthropogenic and pre-industrial fluxes. Hence they need to be adjusted for the pre-industrial flux of CO<sub>2</sub> from the land to the ocean that is part of the natural carbon cycle before they can be compared with SOCEAN and SLAND from process models. See Table 4 for references.

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