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The global carbon budget 1959–2011

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Abstract. Accurate assessments of anthropogenic carbon dioxide (CO_2) emissions and their redistribution among the atmosphere, ocean, and terrestrial biosphere is important to better understand the global carbon cycle, support the climate policy process, and project future climate change. Present-day analysis requires the combination of a range of data, algorithms, statistics and model estimates and their interpretation by a broad scientific community. Here we describe datasets and a methodology developed by the global carbon cycle science community to quantify all major components of the global carbon budget, including their uncertainties. We discuss changes compared to previous estimates, consistency within and among components, and methodology and data limitations. CO_2 emissions from fossil fuel combustion and cement production (E_{FF}) are based on energy statistics, while emissions from Land-Use Change (E_{LUC}), including deforestation, are based on combined evidence from land cover change data, fire activity in regions undergoing deforestation, and models. The global atmospheric CO_2 concentration is measured directly and its rate of growth (G_{ATM}) is computed from the concentration. The mean ocean CO_2 sink (S_{OCEAN}) is based on observations from the 1990s, while the annual anomalies and trends are estimated with ocean models. Finally, the global residual terrestrial CO_2 sink (S_{LAND}) is estimated by the difference of the other terms. For the last decade available (2002–2011), E_{FF} was 8.3 ± 0.4 PgC yr^{-1}, E_{LUC} 1.0 ± 0.5 PgC yr^{-1}, G_{ATM} 4.3 ± 0.1 PgC yr^{-1}, S_{OCEAN} 2.5 ± 0.5 PgC yr^{-1}, and S_{LAND} 2.6 ± 0.8 PgC yr^{-1}. For year 2011 alone, E_{FF} was 9.5 ± 0.5 PgC yr^{-1}, 3.0 percent above 2010, reflecting a continued trend in these emissions; E_{LUC} was 0.9 ± 0.5 PgC yr^{-1}, approximately constant throughout the decade; G_{ATM} was 3.6 ± 0.2 PgC yr^{-1}, S_{OCEAN} was 2.7 ± 0.5 PgC yr^{-1}, and S_{LAND} was 4.1 ± 0.9 PgC yr^{-1}. G_{ATM} was low in 2011 compared to the 2002–2011 average because of a high uptake by the land probably in response to natural climate variability associated to La Niña conditions in the Pacific Ocean. The global atmospheric CO_2 concentration reached 391.31 ± 0.13 ppm at the end of year 2011. We estimate that E_{FF} will have increased by 2.6 % (1.9–3.5 %) in 2012 based on projections of gross world product and recent changes in the carbon intensity of the economy. All uncertainties are reported as ±1 sigma (68 % confidence assuming Gaussian error distributions that the real value lies within the given interval), reflecting the current capacity to characterise the annual estimates of each component of the global carbon budget. This paper is intended to provide a baseline to keep track of annual carbon budgets in the future.

All data presented here can be downloaded from the Carbon Dioxide Information Analysis Center (doi:10.3334/CDIAC/GCP_V2013).

1 Introduction

The concentration of carbon dioxide (CO_2) in the atmosphere has increased from approximately 278 parts per million (ppm) in 1750, the beginning of the Industrial Era, to 391.31 at the end of 2011 (Conway and Tans, 2012). This increase was caused initially mainly by the anthropogenic release of carbon to the atmosphere from deforestation and other land-use change activities. Emissions from fossil fuel combustion started before the Industrial Era and became the dominant source of anthropogenic emissions to the atmosphere from around 1920 until present. Anthropogenic emissions occur on top of an active natural carbon cycle that circulates carbon between the atmosphere, ocean, and terrestrial biosphere reservoirs on timescales from days to many millennia, while geologic reservoirs have even longer timescales (Archer et al., 2009).

The "global carbon budget" presented here refers to the mean, variations, and trends in the anthropogenic perturbation of CO_2 in the atmosphere. It quantifies the input of CO_2 to the atmosphere by emissions from human activities, the growth of CO_2 in the atmosphere, and the resulting changes in land and ocean carbon fluxes directly in response to increasing atmospheric CO_2 levels and indirectly in response to climate change and climate variability, and other anthropogenic and natural changes. An understanding of this perturbation budget over time and the underlying variability and trends of the natural carbon cycle are necessary to understand and quantify climate-carbon feedbacks. This also allows potentially earlier detection of any approaching discontinuities or tipping points of the carbon cycle in response to anthropogenic changes (Falkowski et al., 2000).

The components of the CO_2 budget that are reported in this paper include separate estimates for (1) the CO_2 emissions from fossil fuel combustion and cement production (E_{FF}); (2) the CO_2 emissions resulting from deliberate human activities on land, including land use; land-use change and forestry (shortened to LUC hereafter; E_{LUC}), (3) the growth rate of CO_2 in the atmosphere (G_{ATM}); and (4) the uptake of CO_2 by the "CO_2 sinks" in the ocean (S_{OCEAN}) and on land (S_{LAND}). The CO_2 sinks as defined here include the response of the land and ocean to elevated CO_2 and changes in climate and other environmental conditions. The emissions and their partitioning among the atmosphere, ocean and land are in balance:

$$E_{FF} + E_{LUC} = G_{ATM} + S_{OCEAN} + S_{LAND}. \quad (1)$$

Equation (1) subsumes, and partly omits, two kinds of processes. The first is the net input of CO_2 to the atmosphere from the chemical oxidation of reactive carbon-containing gases, primarily methane (CH_4), carbon monoxide (CO), and volatile organic compounds such as terpene and isoprene, which we quantify here for the first time. The second process involves anthropogenic perturbations to carbon cycling in inland freshwaters, estuaries, and coastal areas that modify both lateral fluxes transported from land ecosystems to the open ocean, "vertical" CO_2 fluxes by outgassing in rivers and estuaries, and the air-sea net exchange of CO_2 in coastal areas (Battin et al., 2008; Aufdenkampe et al., 2011). These flows are omitted in the absence of details on the natural versus anthropogenic terms of these facets of the carbon cycle. The inclusion of these fluxes of anthropogenic CO_2 would affect the estimates of S_{LAND} and perhaps S_{OCEAN} in Eq. (1), but not G_{ATM}.

The CO_2 budget has been assessed by the Intergovernmental Panel on Climate Change (IPCC) in all assessment reports (Watson et al., 1990; Schimel et al., 1995; Prentice et al., 2001; Denman et al., 2007), and by others (Conway and Tans, 2012). These included budget estimates for the decades of the 1980s, 1990s and, most recently, the period 2000–2005. The IPCC methodology has been adapted and used by the Global Carbon Project (GCP, www.globalcarbonproject.org), who have coordinated a cooperative community effort for the annual publication of global carbon budgets up to year 2005 (Raupach et al., 2007; including fossil emissions only), year 2006 (Canadell et al., 2007), year 2007 (published online; http://lgmacweb.env.uea.ac.uk/lequere/co2/2007/carbon_budget_2007.htm), year 2008 (Le Quéré et al., 2009), year 2009 (Friedlingstein et al., 2010), and most recently, year 2010 (Peters et al., 2012a). Each of these papers updated previous estimates with the latest available information for the entire time series. From 2008, these publications projected fossil fuel emissions for one additional year using the projected World Gross Domestic Product and estimated changes in the carbon intensity of the economy.

We adopt a range of ±1 standard deviation (sigma) to report the uncertainties in our annual estimates, representing a likelihood of 68 % that the true value lies within the provided range, assuming that the errors have a Gaussian distribution. This choice reflects the difficulty of characterising the uncertainty in the CO_2 fluxes between the atmosphere and the ocean and land reservoirs individually, as well as the difficulty to update the CO_2 emissions from LUC, particularly on an annual basis. A 68 % likelihood provides an indication of our current capability to quantify each term and its uncertainty given the available information. For comparison, the Fourth Assessment Report of the IPCC (AR4) generally reported 90 % uncertainty for large datasets whose uncertainty is well characterised, or for long time intervals less affected by year-to-year variability. This includes, for instance, attribution statements associated with recorded warming levels since the pre-industrial period. The 90 % number corresponds to the IPCC language of "very likely" or "very high confidence represents at least a 9 out of 10 chance"; our 68 % value is near the 66 % which the IPCC reports as "likely". The uncertainties reported here combine statistical analysis of the underlying data and expert judgement of the likelihood of results lying outside this range. The limitations of current information are discussed in the paper.

All units are presented in petagrammes of carbon (PgC, 10^{15} gC), which is the same as gigatonnes of carbon (GtC). Units of gigatonnes of CO_2 (or billion tonnes of CO_2) used in policy circles are equal to 3.67 multiplied by the value in units of PgC.

This paper provides a detailed description of the datasets and methodology used to compute the global carbon budget and associated uncertainties for the period 1959–2011. It presents the global carbon budget estimates by decade since the 1960s, including the last decade (2002–2011), the results for the year 2011, and a projection of E_{FF} for year 2012. It is intended that this paper will be updated every year using the format of "living reviews" to help keep track of new versions of the budget that result from new data, revision of data, and changes in methodology. Additional materials associated with the release of each new version will be posted at the Global Carbon Project (GCP) website (http://www.globalcarbonproject.org/carbonbudget). With this approach, we aim to provide transparency and traceability in reporting indicators and drivers of climate change.

2 Methods

The original data and measurements used to complete the global carbon budget are generated by multiple organizations and research groups around the world. The effort presented here is thus mainly one of synthesis, where results from individual groups are collated, analysed and evaluated for consistency. Descriptions of the measurements, models, and methodologies follow below and in depth descriptions of each component are described elsewhere (e.g. Andres et al., 2012; Houghton et al., 2012).

2.1 CO_2 emissions from fossil fuel combustion and cement production (E_{FF})

2.1.1 Fossil fuel and cement emissions and their uncertainty

The calculation of global and national CO_2 emissions from fossil fuel combustion, including gas flaring and cement production (E_{FF}), relies primarily on energy data, specifically data on hydrocarbon fuels, collated and archived by several organisations (Andres et al., 2012), including the Carbon Dioxide Information Analysis Center (CDIAC), the International Energy Agency (IEA), the United Nations (UN), and the United States Department of Energy (DoE) Energy Information Administration (EIA). We use the emissions estimated by the CDIAC (http://cdiac.ornl.gov) which are based primarily on energy data provided by the UN Statistics Division (UN, 2012a, b; Table 1), and are typically available 2–3 yr after the close of a given year. CDIAC also provides the only dataset that extends back in time to 1751 with consistent and well-documented emissions from all fossil fuels, cement production, and gas flaring for all countries; this makes

Table 1. Data sources used to compute each component of the global carbon budget.

Component	Process	Data source	Data reference
E_{FF}	Fossil fuel combustion and gas flaring	UN Statistics Division to 2009 BP for 2010–2011	UN (2012a, b) BP (2012)
	Cement production	US Geological Survey	van Oss (2011) US Geological Survey (2012)
	Consumption-based country emissions	Global Trade and Analysis Project (GTAP)	Narayanan et al. (2012)
E_{LUC}	Land cover change (deforestation, afforestation, and forest regrowth)	Forest Resource Assessment (FRA) of the Food and Agriculture Organisation (FAO)	FAO (2010)
	Wood harvest	FAO Statistics Division	FAOSTAT (2010)
	Shifting agriculture	FAO FRA and Statistics Division	FAOSTAT (2010) FAO (2010)
	Peat fires and interannual variability from climate–land management interactions	Global Fire Emissions Database (GFED3)	van der Werf et al. (2010)
G_{ATM}	Change in CO_2 concentration	1959–1980: CO_2 Program at Scripps Institution of Oceanography and other research groups	Keeling et al. (1976)
		1980–2011: US National Oceanic and Atmospheric Administration Earth System Research Laboratory	Conway and Tans (2012) and Ballantyne et al. (2012)
S_{OCEAN}	Uptake of anthropogenic CO_2	1990–1999 average: indirect estimates based on CFCs, atmospheric O_2, and other tracer observations	Manning and Keeling (2006); McNeil et al. (2003); Mikaloff Fletcher et al. (2006) as assessed by the IPCC (Denman et al., 2007)
	Impact of increasing atmospheric CO_2, and climate change and variability	Ocean models	Le Quéré et al. (2009) and Table 3
S_{LAND}	Response of land vegetation to: increasing atmospheric CO_2 concentration Climate change and variability Other environmental changes	Budget residual	

the dataset a unique resource for research of the carbon cycle during the fossil fuel era. For this paper, we use CDIAC emissions data from the period 1959–2009, and preliminary estimates based on the BP annual energy review for extrapolation of emissions in 2010 and 2011 (BP, 2012). BP's sources for energy statistics overlap with those of the UN data but are compiled more rapidly, using a smaller group of mostly developed countries and assumptions for missing data. We use the BP values only for the year-to-year rate of change, because the rates of change are less uncertain than the absolute values. The preliminary estimates are replaced by the more complete CDIAC data when available. Past experience shows that projections based on the BP rate of change provide reliable estimates for the two most recent years when full data are not yet available from the UN (see Sect. 3.2).

Emissions from cement production are based on cement data from the US Geological Survey (van Oss, 2011) up to year 2009, and from preliminary data for 2010 and 2011 (US Geological Survey, 2012). Emission estimates from gas flaring are calculated in a similar manner as those from solid, liquid, and gaseous fuels, and rely on the UN Energy Statistics to supply the amount of flared fuel. For emission years 2010 and 2011, flaring estimates are assumed constant from the emission year 2009 UN-based data. The basic data on gas flaring have large uncertainty. Fugitive emissions of CH_4 from the so-called upstream sector (coal mining, oil extraction, gas extraction and distribution) are not included in the accounts of CO_2 emissions except to the extent that they get captured in the UN energy data and counted as gas "flared or lost". The UN data are not able to distinguish between gas that is flared or vented.

When necessary, fuel masses/volumes are converted to fuel energy content using coefficients provided by the UN and then to CO_2 emissions using conversion factors that take into account the relationship between carbon content and heat content of the different fuel types (coal, oil, gas, gas flaring) and the combustion efficiency (to account, for example, for soot left in the combustor or fuel otherwise lost or discharged without oxidation). In general, CO_2 emissions for equivalent energy consumptions are about 30 % higher for coal compared to oil, and 70 % higher for coal compared to gas (Marland et al., 2007). These calculations are based on the mass flows of carbon and assume that the carbon discharged, such as CO or CH_4, will soon be oxidized to CO_2 in the atmosphere and hence counts the carbon mass with CO_2 emissions.

Emissions are estimated for 1959–2011 for 129 countries and regions. The disaggregation of regions (e.g. the former Soviet Union prior to 1992) is based on the shares of emissions in the first year after the countries were disaggregated.

Estimates of CO_2 emissions show that the global total of emissions is not equal to the sum of emissions from all countries. This is largely attributable to combustion of fuels used in international shipping and aviation, where the emissions are included in the global totals but are not attributed to individual countries. In practice, the emissions from international bunker fuels are calculated based on where the fuels were loaded, but they are not included with national emissions estimates. Smaller differences also occur because globally, the sum of imports in all countries is not equivalent to the sum of exports, due to differing treatment of oxidation of non-fuel uses of hydrocarbons (e.g. as solvents, lubricants, feedstocks, etc.).

The uncertainty of the annual fossil fuel and cement emissions for the globe has been estimated at ±5 % (scaled down from the published ±10 % at ±2 sigma to the use of ±1 sigma bounds reported here; Andres et al., 2012). This includes an assessment of the amounts of fuel consumed, the carbon contents of fuels, and the combustion efficiency. While in the budget we consider a fixed uncertainty of ±5 % for all years, in reality the uncertainty, as a percentage of the emissions, is growing with time because of the larger share of global emissions from non-Annex B countries with weaker statistical systems (Marland et al., 2009). For example, the uncertainty in Chinese emissions estimates has been estimated at around ±10 % (±1 sigma; Gregg et al., 2008). Generally, emissions from mature economies with good statistical bases have an uncertainty of only a few percent (Marland, 2008). Further research is needed before we can quantify the time evolution of the uncertainty.

2.1.2 Emissions embodied in goods and services

National emissions inventories take a territorial (production) perspective by "include[ing] all greenhouse gas emissions and removals taking place within national (including administered) territories and offshore areas over which the country has jurisdiction" (from the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories). That is, emissions are allocated to the country where and when the emissions actually occur. The emission inventory of an individual country does not include the emissions from the production of goods and services produced in other countries (e.g. food and clothes) that are used for national consumption. The difference between the standard territorial emission inventories and consumption-based emission inventories is the net transfer (exports minus imports) of emissions from the production of internationally traded goods and services. Complementary emission inventories that allocated emissions to the final consumption of goods and services (e.g. Davis and Caldeira, 2010) provide additional information that can be used to understand emission drivers, quantify emission leakages between countries, and potentially design more effective and efficient climate policy.

We estimate consumption-based emissions by enumerating the global supply chain using a global model of the economic relationships between sectors in every country (Peters et al., 2011a). Due to availability of the input data, detailed estimates are made for the years 1997, 2001, 2004, and 2007 (an extension of Peters et al., 2011b) using economic and trade data from the Global Trade and Analysis Project (GTAP; Narayanan et al., 2012). The results cover 57 sectors and up to 129 countries and regions. The results are extended into an annual time series from 1990 to the latest year of the fossil-fuel emissions or GDP data (2010 in this budget), using GDP data by expenditure (from the UN Main Aggregates database; UN, 2012c) and time series of trade data from GTAP (Narayanan et al., 2012). We do not provide an uncertainty estimate for these emissions, but based on model comparisons and sensitivity analysis, they are unlikely to be significantly larger than for the territorial emission estimates (Peters et al., 2012b). Uncertainty is expected to increase for more detailed results (Peters et al., 2011b; e.g. the results for

Annex B will be more accurate than the sector results for an individual country).

It is important to note that the consumption-based emissions defined here consider directly the carbon embodied in traded goods and services, but not the trade in unoxidised fossil fuels (coal, oil, gas). In our consumption-based inventory, emissions from traded fossil fuels accrue to the country where the fuel is burned or consumed, not the exporting country from which it was extracted (Davis et al., 2011).

The consumption-based emission inventories in this carbon budget have several improvements over previous versions (Peters et al., 2011b, 2012a). The detailed estimates for 2004 and 2007 are based on an updated version of the GTAP database (Narayanan et al., 2012). We estimate the sector level CO_2 emissions using our own calculations based on the GTAP data and methodology, but scale the national totals to match the CDIAC estimates from the carbon budget. We do not include international transportation in our estimates. The time series of trade data provided by GTAP covers the period 1995–2009 and our methodology uses the trade shares of this dataset. For the period 1990–1994 we assume the trade shares of 1995, while in 2010 we assume the trade shares of 2008, since 2009 was heavily affected by the global financial crisis. We identified errors in the trade shares of Taiwan and the Netherlands in 2008 and 2009, and for these two countries, the trade shares for 2008–2010 are based on the 2007 trade shares.

These data do not contribute to the global average terms in Eq. (1), but are relevant to the anthropogenic carbon cycle, as they reflect the movement of carbon across the Earth's surface in response to human needs (both physical and economic). Furthermore, if national and international climate policies continue to develop in an unharmonious way, then the trends reflected in these data will need to be accommodated by those developing policies.

2.1.3 Emissions projections for the current year

Energy statistics are normally available around June for the previous year. We use the close relationship between the growth in world Gross Domestic Product (GDP) and the growth in global emissions (Raupach et al., 2007) to project emissions for the current year. This is based on the so-called Kaya (also called IPAT) identity, whereby E_{FF} is decomposed by the product of GDP and the fossil fuel carbon intensity of the economy (I_{FF}) as follows:

$$E_{\mathrm{FF}} = \mathrm{GDP} \cdot I_{\mathrm{FF}}; \tag{2}$$

taking a time derivative of this equation gives:

$$\frac{\mathrm{d}E_{\mathrm{FF}}}{\mathrm{d}t} = \frac{\mathrm{d}(\mathrm{GDP} \cdot I_{\mathrm{FF}})}{\mathrm{d}t}; \tag{3}$$

and applying the rules of calculus, assuming that GDP and I_{FF} are independent:

$$\frac{\mathrm{d}E_{\mathrm{FF}}}{\mathrm{d}t} = \frac{\mathrm{dGDP}}{\mathrm{d}t} \cdot I_{\mathrm{FF}} + \mathrm{GDP} \cdot \frac{\mathrm{d}I_{\mathrm{FF}}}{\mathrm{d}t}; \tag{4}$$

finally, dividing Eqs. (4) by (2) gives:

$$\frac{1}{E_{\mathrm{FF}}}\frac{\mathrm{d}E_{\mathrm{FF}}}{\mathrm{d}t} = \frac{1}{\mathrm{GDP}}\frac{\mathrm{dGDP}}{\mathrm{d}t} + \frac{1}{I_{\mathrm{FF}}}\frac{\mathrm{d}I_{\mathrm{FF}}}{\mathrm{d}t}, \tag{5}$$

where the left hand term is the relative growth rate of E_{FF}, and the right hand terms are the relative growth rates of GDP and I_{FF}, respectively, which can simply be added linearly to give overall growth rate. The growth rates are reported in percent below by multiplying each term by 100. Because preliminary estimates of annual change in GDP are made well before the end of a calendar year, making assumptions on the growth rate of I_{FF} allows us to make projections of the annual change in CO_2 emissions well before the end of a calendar year.

2.1.4 Growth rate in emissions

We report the annual growth rate in emissions for adjacent years in percent by calculating the difference between the two years and then comparing to the emissions in the first year: $[(E_{\mathrm{FF}}(t_0+1) - E_{\mathrm{FF}}(t_0))/E_{\mathrm{FF}}(t_0)] \cdot 100$. This is the simplest method to characterise a one-year growth compared to the previous year. This has strong links with the more general way in which society presents economic change in journalistic circles, most often a comparison of present-day economic activity compared to the previous year.

The growth rate of E_{FF} over time periods of greater than one year can be re-written using its logarithm equivalent as follows:

$$\frac{1}{E_{\mathrm{FF}}}\frac{\mathrm{d}E_{\mathrm{FF}}}{\mathrm{d}t} = \frac{\mathrm{d}(\ln E_{\mathrm{FF}})}{\mathrm{d}t}. \tag{6}$$

Here we calculate growth rates in emissions for multi-year periods (e.g. a decade) by fitting a linear trend to ln (E_{FF}) in Eq. (6), reported in percent per year. We fit the logarithm of E_{FF} rather than E_{FF} directly because this method ensures that computed growth rates satisfy Eq. (5). This method differs from previous papers (Canadell et al., 2007; Le Quéré et al., 2009), who computed the fit to E_{FF} and divided by average E_{FF} directly, but the difference is very small (<0.05 percent) in the case of E_{FF}.

2.2 CO_2 emissions from land use, land-use change and forestry (E_{LUC})

Net LUC emissions reported in our annual budget (E_{LUC}) include CO_2 fluxes from afforestation, deforestation, logging (forest degradation and harvest activity), shifting cultivation (cycle of cutting forest for agriculture then abandoning), regrowth of forests following wood harvest or abandonment of agriculture, fire-based peatland emissions and other land management practices (Table 2). Our annual estimate combines information from a bookkeeping model (Sect. 2.2.1) primarily based on forest area change and biomass data from

Table 2. Comparison of the processes included in the E_{LUC} of the global carbon budget and the DGVMs. See Table 3 for model references.

	CO_2 budget	VISIT	ISAM-HYDE	LPJmL	LPJ-Bern
Deforestation, afforestation, forest regrowth after abandonment of agriculture	yes	yes	yes	yes	yes
Wood harvest and forest degradation	yes	no	yes	no	no
Shifting cultivation	yes	yes	no	no	no
Cropland harvest	yes	no	no	no	yes
Peat fires	from 1997	no	no	no	no
Fire suppression	for US only	no	no	no	no
Management–Climate interactions	from 1997	no	no	no	no
Climate change and variability	no	climate change is present but decadal mean response is used for regrowing uptake	climate variability present but not corresponding to observed years	yes	yes
CO_2 fertilisation	no	yes	yes	yes	yes
Nitrogen dynamics	no	no	yes	no	no

the Forest Resource Assessment (FRA) of the Food and Agriculture Organisation (FAO; Houghton, 2003) published at intervals of five years, with annual emissions estimated from satellite-based fire activity in deforested areas (Sect. 2.2.2; van der Werf et al., 2010). The bookkeeping model is used mainly to quantify the mean E_{LUC} over the time period of the available data, and the satellite-based method to distribute these emissions annually. The satellite-based emissions are available from year 1997 onwards only. We calculate the global anomaly in satellite-based emissions over deforested regions, compared to the 1997–2011 time period, and add this to average E_{LUC} estimated using the bookkeeping method. We thus assume that all land management activities apart from deforestation do not vary significantly on a year-to-year basis. Other sources of interannual variability (e.g. the impact of climate variability on regrowth) are accounted for in S_{LAND}. We also use independent estimates from Dynamic Global Vegetation Models (Sect. 2.2.3) to help quantify the uncertainty in global E_{LUC}.

2.2.1 Bookkeeping method

E_{LUC} calculated using a bookkeeping method (Houghton, 2003) keeps track of the carbon stored in vegetation and soils before deforestation or other land-use change, and the changes in forest age classes, or cohorts, of disturbed lands after land-use change. It tracks the CO_2 emitted to the atmosphere over time due to decay of soil and vegetation carbon in different pools, including wood products, pools after logging and deforestation. It also tracks the regrowth of vegetation and build-up of soil carbon pools following land-use change. It considers transitions between forests, pastures and cropland, shifting cultivation, degradation of forests where a fraction of the trees is removed, abandonment of agricultural land, and forest management such as logging and fire management. In addition to tracking logging debris on the forest floor, the bookkeeping model tracks the fate of carbon contained in harvested wood products that is eventually emitted back to the atmosphere as CO_2, although a detailed treatment of the lifetime in each product pool is not performed (Earles et al., 2012). Harvested wood products are partitioned into three pools with different turnover times. All fuelwood is assumed to be burned in the year of harvest ($1.0\,yr^{-1}$). Pulp and paper products are oxidized at a rate of $0.1\,yr^{-1}$. Timber is assumed to be oxidized at a rate of $0.01\,yr^{-1}$, and elemental carbon decays at $0.001\,yr^{-1}$. The general assumptions about partitioning wood products among these pools are based on national harvest data.

The primary land cover change and biomass data for the bookkeeping model analysis is the FAO FRA 2010 (FAO, 2010; Table 1), which is based on countries' self-reporting of statistics on forest cover change and management partially combined with satellite data in more recent assessments. Changes in land cover other than forest are based on annual, national changes in cropland and pasture areas reported by the FAO Statistics Division (FAOSTAT, 2010). The LUC dataset is non-spatial and aggregated by regions. The carbon stocks on land (biomass and soils), and their response

Table 3. References for the process models included in Fig. 3.

Model name	Reference
Dynamic Global Vegetation Models providing E_{LUC}	
VISIT	Kato et al. (2013) Climate forcing is changed to use CRU TS3.10.01 up to the year 2009
ISAM-HYDE	Jain et al. (2013)
LPJmL	Poulter et al. (2010)
LPJ-Bern	Stocker et al. (2011); Strassmann et al. (2008)
Dynamic Global Vegetation Models providing S_{LAND}	
Community Land Model 4CN	Lawrence et al. (2011)
Hyland	Levy et al. (2004)
JULES	Clark et al. (2011); Cox (2001)
LPJ	Sitch et al. (2003)
LPJ-GUESS	Smith et al. (2001); Ahlström et al. (2012) and references therein
O-CN	Zaehle et al. (2011)
Orchidee	Krinner et al. (2005)
Sheffield-DGVM	Woodward and Lomas (2004)
VEGAS	Zeng et al. (2005)
Ocean Biogeochemistry Models providing S_{OCEAN}	
NEMO-PlankTOM5	Buitenhuis et al. (2010) with no nutrient restoring below the mixed layer depth
LSCE	Aumont and Bopp (2006)
CCSM-BEC	Doney et al. (2009)
MICOM-HAMOCC	Assmann et al. (2010) with updates to the physical model as described in Tjiputra et al. (2013)

functions subsequent to LUC, are based on averages per land cover type, per biome and per region. Similar results were obtained using forest biomass carbon density based on satellite data (Baccini et al., 2012). The bookkeeping model does not include land ecosystems' transient response to changes in climate, atmospheric CO_2 and other environmental factors, but the growth/decay curves are based on contemporary data that will implicitly reflect the effects of CO_2 and climate at that time. Results from the bookkeeping method are available from 1850 to 2010.

2.2.2 Fire-based method

LUC CO_2 emissions calculated from satellite-based fire activity in deforested areas (van der Werf et al., 2010) provide information that is complementary to the bookkeeping approach. Although they do not provide a direct estimate of E_{LUC}, as they do not include processes such as respiration, wood harvest, wood products or forest regrowth, they do provide insight on the year-to-year variations in E_{LUC} that result from the interactions between climate and human activity (e.g. there is more burning and clearing of forests in dry years). The "deforestation fire emissions" assumes an important role of fire in removing biomass in the deforestation process, and thus can be used to infer direct CO_2 emissions from deforestation using satellite-derived data on fire activity in regions with active deforestation (legacy emissions such as decomposition from ground debris or soils are missed by this method). The method requires information on the fraction of total area burned associated with deforestation versus other types of fires, and can be merged with information on biomass stocks and the fraction of the biomass lost in a deforestation fire to estimate CO_2 emissions. The satellite-based fire emissions are limited to the tropics, where fires result mainly from human activities. Tropical deforestation is the largest and most variable single contributor to E_{LUC}.

Here we used annual estimates from the Global Fire Emissions Database (GFED3), available from http://www.globalfiredata.org. Burned area from (Giglio et al., 2010) is merged with active fire retrievals to mimic more sophisticated assessments of deforestation rates in the pan-tropics (van der Werf et al., 2010). This information is used as input data in a modified version of the satellite-driven CASA biogeochemical model to estimate carbon emissions, keeping track of what fraction was due to deforestation (van der Werf et al., 2010). The CASA model uses different assumptions to compute delay functions compared to the bookkeeping model, and does not include historical emissions or regrowth from land-use change prior to the availability of satellite data.

Comparing coincident CO emissions and their atmospheric fate with satellite-derived CO concentrations allows for some validation of this approach (e.g. van der Werf et al., 2008). In this paper, we only use emissions based on deforestation fires to quantify the interannual variability in E_{LUC}. Results from the fire-based method are available from 1997 to 2011.

2.2.3 Dynamic Global Vegetation Models (DGVMs) and uncertainty assessment for LUC

Net LUC CO_2 emissions have also been estimated using DGVMs that explicitly represent some processes of vegetation growth, mortality and decomposition associated with natural cycles and also provide a response to prescribed land cover change and climate and CO_2 drivers (Table 2). The DGVMs calculate the dynamic evolution of biomass and soil carbon pools that are affected by environmental variability and change in addition to LUC transitions each year. They are independent from the other budget terms except for their use of atmospheric CO_2 concentration to calculate the fertilization effect of CO_2 on primary production. The DGVMs do not exactly provide E_{LUC} as defined in this paper because they represent fewer processes resulting directly from human activities on land, but include the vegetation and soil response to increasing atmospheric CO_2 levels, to climate variability and change (in three models), in addition to atmospheric N deposition in the presence of nitrogen limitation (in one model; Table 2). Nevertheless all methods represent deforestation, afforestation and regrowth, three of the most important components of E_{LUC}, and thus the model spread can help quantify the uncertainty in E_{LUC}.

The DGVMs used here prescribe land cover change from the HYDE spatially gridded datasets updated to 2009 (Goldewijk et al., 2011; Hurtt et al., 2011), which is based on FAO statistics of change in agricultural areas (FAOSTAT, 2010) with assumptions made about change in forest or other land cover as a result of agricultural area change. The changes in agricultural areas are then implemented within each model (for instance, an increased cropland fraction in a grid cell can either use pasture land, or forest, the latter resulting into deforestation). This differs with the dataset used in the bookkeeping method (Houghton, 2003 and updates), which is based on forest area change statistics (FAO, 2010). The DGVMs also represent a different methodology of calculating carbon fluxes, and thus provide an independent assessment of LUC emissions to the bookkeeping results (Sect. 2.2.1).

Differences between estimates thus originate from three main sources, firstly the land cover change dataset, secondly different approaches in models, and thirdly different process boundaries (Table 2). Four different DGVM estimates are presented here and used to explore the uncertainty in LUC annual emissions (Jain et al., 2013; Kato et al., 2013; Poulter et al., 2010; Stocker et al., 2011). While many published DGVM LUC emissions estimates exist, these model runs were driven by a consistently updated HYDE LUC dataset up to year 2009.

We examine the standard deviation of the annual estimates to assess the uncertainty in E_{LUC}. The standard deviation across models in each year ranged from 0.09 to 0.70 $PgC\,yr^{-1}$, with an average of 0.42 $PgC\,yr^{-1}$ from 1960 to 2009. One of the four models (Jain et al., 2013) was used with three different LUC datasets (including HYDE and FAO FRA2005; Jain et al., 2013; Meiyappan and Jain, 2012). The standard deviation for decadal means in these three model runs was $\pm 0.19\,PgC\,yr^{-1}$ for 1990 to 2005, and ranged from 0.06 to 0.70 $PgC\,yr^{-1}$ for annual estimates with an average of $\pm 0.27\,PgC\,yr^{-1}$ from 1960 to 2005. Assuming the two sources of uncertainty are independent, we can combine them using standard error propagation rules. Taking the quadratic sum of the mean annual standard deviation across the four DGVMs (0.42 $PgC\,yr^{-1}$) and the standard deviation due to different land cover change datasets (0.27 $PgC\,yr^{-1}$) we get a combined standard deviation of 0.5 $PgC\,yr^{-1}$.

We use the combined standard deviation $\pm 0.5\,PgC\,yr^{-1}$ as a quantitative measure of uncertainty for annual emissions, and to reflect our best value judgment that there is at least 68 % chance (± 1 sigma) that the true LUC emission lies within the given range, for the range of processes considered here. However, we note that missing processes such as the decomposition of drained tropical peatlands (Ballhorn et al., 2009; Hooijer et al., 2010) could introduce biases which are not quantified here, while the inclusion of the impact of climate variability on land processes by some DGVMs (Table 2) may inflate the standard deviation in annual estimates of LUC emissions compared to our definition of E_{LUC}. The uncertainty of $\pm 0.5\,PgC\,yr^{-1}$ is slightly lower than that of $\pm 0.7\,PgC\,yr^{-1}$ estimated in the 2010 CO_2 budget release (Friedlingstein et al., 2010) based on expert assessment of the available estimates. A more recent expert assessment of uncertainty for the decadal mean based on a larger set of published model and uncertainty studies estimated $\pm 0.5\,PgC\,yr^{-1}$ (Houghton et al., 2012) which partly reflects improvements in data on forest area change using satellite data, and partly more complete understanding and representation of processes in models. We adopt $\pm 0.5\,PgC\,yr^{-1}$ here for the decadal averages presented Table 4.

The errors in the decadal mean estimates from the DGVM ensemble are likely correlated between decades. They come from (1) system boundaries (e.g. not counting forest degradation in some models), which cause a bias that makes decadal estimates perfectly correlated (Gasser and Ciais, 2013; Table 2); (2) common land cover change input data which cause a bias, though if a different input dataset is used each decade, decadal fluxes from DGVMs may be partly decorrelated; (3) model structural errors, which cause bias that correlate decadal estimates. In addition, errors arising from uncertain DGVM parameter values would be random but they are not accounted for in this study, since no DGVM provided an ensemble of runs with perturbed parameters.

Table 4. Decadal mean in the five components of the anthropogenic CO_2 budget for the periods 1960–1969, 1970–1979, 1980–1989, 1990–1999, 2000–2009 and the last decade available. All values are in $PgC\,yr^{-1}$. All uncertainties are reported as ±1 sigma (68 % confidence assuming Gaussian error distributions that the real value lies within the given interval).

	mean ($PgC\,yr^{-1}$)					
	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009	2002–2011
Emissions						
Fossil fuel combustion and cement production (E_{FF})	3.1 ± 0.2	4.7 ± 0.2	5.5 ± 0.3	6.4 ± 0.3	7.8 ± 0.4	8.3 ± 0.4
Land-Use Change emissions (E_{LUC})	1.5 ± 0.5	1.3 ± 0.5	1.4 ± 0.5	1.6 ± 0.5	1.0 ± 0.5	1.0 ± 0.5
Partitioning						
Atmospheric growth rate (G_{ATM})	1.7 ± 0.1	2.8 ± 0.1	3.4 ± 0.1	3.1 ± 0.1	4.0 ± 0.1	4.3 ± 0.1
Ocean sink (S_{OCEAN})	1.2 ± 0.5	1.5 ± 0.5	1.9 ± 0.5	2.2 ± 0.4	2.4 ± 0.5	2.5 ± 0.5
Residual terrestrial sink (S_{LAND})	1.7 ± 0.7	1.7 ± 0.8	1.6 ± 0.8	2.7 ± 0.8	2.4 ± 0.8	2.6 ± 0.8

2.3 Atmospheric CO_2 growth rate (G_{ATM})

2.3.1 Global atmospheric CO_2 growth rate estimates

The atmospheric CO_2 growth rate is provided by the US National Oceanic and Atmospheric Administration Earth System Research Laboratory (Conway and Tans, 2012), which is updated from Ballantyne et al. (2012). For the 1959–1980 period, the global growth rate is based on measurements of atmospheric CO_2 concentration averaged from the Mauna Loa and South Pole stations, as observed by the CO_2 Program at Scripps Institution of Oceanography (Keeling et al., 1976). For the 1980–2011 time period, the global growth rate is based on the average of multiple stations selected from the marine boundary layer sites (Ballantyne et al., 2012), after fitting each station with a smoothed curve as a function of time, and averaging by latitude band (Masarie and Tans, 1995). The annual growth rate is estimated from atmospheric CO_2 concentration by taking the average of the most recent and December–January months corrected for the average seasonal cycle and subtracting this same average one year earlier. The growth rate in units of $ppm\,yr^{-1}$ is converted to fluxes by multiplying by a factor of 2.123 PgC per ppm (Enting et al., 1994) for comparison with the other components.

The uncertainty around the annual growth rate based on the multiple stations dataset ranges between 0.11 and 0.72 $PgC\,yr^{-1}$, with a mean of 0.61 $PgC\,yr^{-1}$ for 1959–1980 and 0.18 $PgC\,yr^{-1}$ for 1980–2011, when a larger set of stations were available. It is based on the number of available stations, and thus takes into account both the measurement errors and data gaps at each station. This uncertainty is larger than the uncertainty of ±0.1 $PgC\,yr^{-1}$ reported for decadal mean growth rate by the IPCC because errors in annual growth rate are strongly anti-correlated in consecutive years leading to smaller errors for longer timescales. The decadal change is computed from the difference in concentration ten years apart based on measurement error of 0.35 ppm (based on offsets between NOAA/ESRL measurements and those of the World Meterological Organisation World Data Center for Greenhouse Gases; NOAA/ESRL, 2012) for the start and end points (the decadal change uncertainty is the sqrt$(2 \times (0.35\,\text{ppm})^2)$/10 yr assuming that each yearly measurement error is independent). This uncertainty is also used in Table 4.

2.3.2 Assessing the contribution of anthropogenic CO and CH_4 to the global anthropogenic CO_2 budget

Emissions of CO and CH_4 to the atmosphere are assumed to be mainly balanced by natural land CO_2 sinks for all biogenic carbon compounds, but small imbalances arise through anthropogenic emissions of fugitive fossil fuel CH_4 and CO, and changes in oxidation rates, e.g. in response to climate variability. These contributions are omitted in Eq. (1), but quantified in this section to highlight the current understanding about their magnitude, and identify the sources of uncertainty. Emissions of CO from combustion processes are included with E_{FF} and E_{LUC} (for example, CO emissions from fires associated with LUC are included in E_{LUC}). However, fugitive anthropogenic emissions of fossil CH_4 (e.g. gas leaks) from the coal, oil and gas upstream sectors are not counted in E_{FF} because these leaks are not inventoried in the fossil fuel statistics as they are not consumed as fuel.

In the absence of anthropogenic change, natural sources of CO and CH_4 from wildfires and CH_4 wetlands are assumed to be balanced by CO_2 uptake by photosynthesis on continental and long timescales (e.g. decadal or longer). Anthropogenic land-use change (e.g. biomass burning for forest clearing or land management, wetland management) and the indirect anthropogenic effects of climate change on wildfires and wetlands result in an imbalance of sources and sinks of carbon. For the purposes of this study, we assume wildfire and wetland emissions of CO and CH_4 are in balance, and that the non-industrial anthropogenic biogenic sources are captured within estimates of emissions of CO_2 from LUC (included in Sect. 2.2). Peatland draining results in a reduction of CH_4 emissions and an increase in CO_2 (not included in modelled estimates presented here). Thus, none of the CO and CH_4 sources above are included in the (anthropogenic) CO_2 budget of this study.

By contrast to biogenic sources, CO and CH_4 emissions from fossil fuel use are not balanced by any recent CO_2 uptake by photosynthesis, and hence represent a net addition of fossil carbon to the atmosphere. This is implicitly included in this study as estimates of CO_2 emissions are based on the total carbon content of the fuel, and the measured CO_2 growth rate includes CO_2 from CO.

This is not the case for anthropogenic fossil CH_4 emission from fugitive emissions during natural gas extraction and transport, and from the coal and oil industry (gas leaks). This emission of carbon to the atmosphere is not included in the fossil fuel CO_2 emissions described in Sect. 2.1. This CH_4 emission is estimated at 0.09 Pg C yr^{-1} (Kirschke et al., 2013). Fossil CH_4 emissions are assumed to be oxidized with a lifetime of 12.4 yr, the e-folding time of an atmospheric perturbation removal (Prater et al., 2012). After one year, 92 % of these emissions remain in the atmosphere as CH_4 and contribute to the observed CH_4 global growth rate, whereas the rest (8 %) get oxidized into CO_2, and contribute to the CO_2 growth rate. Given that anthropogenic fossil fuel CH_4 emissions represent a fraction of 15 % of the total global CH_4 source (Kirschke et al., 2013), we assumed that a fraction of 0.15 times 0.92 of the observed global growth rate of CH_4 of 6 Tg C-CH_4 yr^{-1} (units of C in CH_4 form) during 2000–2009 is due to fossil CH_4 sources. Therefore, annual fossil fuel CH_4 emissions contribute 0.8 Tg C-CH_4 yr^{-1} to the CH_4 growth rate and 0.8 Tg C-CO_2 yr^{-1} (units of C in CO_2 form) to the CO_2 growth rate. Summing up the effect of fossil fuel CH_4 emissions from each previous year during the past 10 yr, a fraction of which is oxidized into CO_2 in the current year, this defines a contribution of 5 Tg C-CO_2 yr^{-1} to the CO_2 growth rate, or about 0.1 %. Thus the effect of anthropogenic fossil CH_4 fugitive emissions and their oxidation to anthropogenic CO_2 in the atmosphere can be assessed to have a negligible effect on the observed CO_2 growth rate, although they do contribute significantly to the global CH_4 growth rate.

2.4 Ocean CO_2 sink

A mean ocean CO_2 sink of 2.2 ± 0.4 PgC yr^{-1} for the 1990s was estimated by the IPCC (Denman et al., 2007) based on three data-based methods (Mikaloff Fletcher et al., 2006; Table 1). Here we adopt this mean CO_2 sink (Manning and Keeling, 2006; McNeil et al., 2003), and compute the trends in the ocean CO_2 sink for 1959–2011 using a combination of five global ocean biogeochemistry models (Table 3). The models 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 models are forced by meteorological reanalysis data and atmospheric CO_2 concentration available for the entire time period. They compute the air-sea flux of CO_2 over grid boxes of 1 to 4 degrees in latitude and longitude. The ocean CO_2 sink for each model is normalised to the observations, by dividing the annual model values by their observed average over 1990–1999, and multiplying this by 2.2 PgC yr^{-1}. This normalisation ensures that the ocean CO_2 sink for the global carbon budget is based on observations, and that the trends and annual values in CO_2 sinks are consistent with model estimates. The ocean CO_2 sink for each year (t) is therefore:

$$S_{\mathrm{OCEAN}}(t) = \frac{1}{n}\sum_{m}\frac{S^{m}_{\mathrm{OCEAN}}(t)}{S^{m}_{\mathrm{OCEAN}}(1990\text{–}1999)}\cdot 2.2\,\mathrm{PgC\,yr^{-1}}, \quad (7)$$

where n is the number of models. We use the four models published in Le Quéré et al. (2009), including updates of Aumont and Bopp (2006), Doney et al. (2009), and Buitenhuis et al. (2010) available to 2011, the model results from Galbraith et al. (2010) available to 2008, and one further model estimate updated from Assman et al. (2010) also available to 2011. The mean ocean CO_2 sink from these models for 1990–1999 ranges between 1.55 and 2.59 PgC yr^{-1}. The standard deviation of the ocean model ensemble averages to 0.14 PgC yr^{-1} during 1980–2011 (with a maximum of 0.22), but it increases as the model ensemble goes back in time, with a standard deviation of 0.3 PgC yr^{-1} across models in the 1960s and 0.49 PgC yr^{-1} in year 1959. We estimate that the uncertainty in the annual ocean CO_2 sink is about ± 0.5 PgC yr^{-1} from the quadratic sum of the data uncertainty of ± 0.4 PgC yr^{-1} and standard deviation across model of up to ± 0.3 PgC yr^{-1}, reflecting both the uncertainty in the mean sink and in the interannual variability as assessed by models.

2.5 Terrestrial CO_2 sink

The difference between the fossil fuel (E_{FF}) and LUC net emissions (E_{LUC}), the atmospheric growth rate (G_{ATM}) and the ocean CO_2 sink (S_{OCEAN}) is attributable to the net sink of CO_2 in terrestrial vegetation and soils (S_{LAND}), within the given uncertainties. Thus, this sink can be estimated either as the residual of the other terms in the mass balance budget but also directly calculated using DGVMs. Note the S_{LAND} term does not include gross land sinks directly resulting from LUC (e.g. regrowth of vegetation) as these are estimated as part of the net land use flux (E_{LUC}). The residual land sink (S_{LAND}) is in part due to the fertilising effect of rising atmospheric CO_2 on plant growth, N deposition and climate change effects such as prolonged growing seasons in northern temperate areas.

2.5.1 Residual of the budget

For 1959–2011, the terrestrial carbon sink was estimated from the residual of the other budget terms:

$$S_{\mathrm{LAND}} = E_{\mathrm{FF}} + E_{\mathrm{LUC}} - (G_{\mathrm{ATM}} + S_{\mathrm{OCEAN}}). \tag{8}$$

The uncertainty in S_{LAND} is estimated annually from the quadratic sum of the uncertainty in the right-hand terms assuming the errors are not correlated. The uncertainty averages to ±0.8 PgC yr^{-1} over 1959–2011, increasing with time to ±0.93 PgC yr^{-1} in 2011. S_{LAND} estimated from the residual of the budget will include, by definition, all the missing processes and potential biases in the other components of Eq. (8).

2.5.2 DGVMs

A comparison of the residual calculation of S_{LAND} in Eq. (8) with outputs from DGVMs similar to those described in Sect. 2.2.3, but designed to quantify S_{LAND} rather than E_{LUC}, provides an independent estimate of the consistency of S_{LAND} with our understanding of the functioning of the terrestrial vegetation in response to CO_2 and climate variability. An ensemble of nine DGVMs are presented here, coordinated by the project "trends and drivers of the regional-scale sources and sinks of carbon dioxide (Trendy)" (Table 3). These DGVMs were forced with changing climate and atmospheric CO_2 concentration, and a fixed contemporary cropland distribution. These models thus include all climate variability and CO_2 effects over land, but do not include the trend in CO_2 sink capacity associated with human activity directly affecting changes in vegetation cover and management. This effect has been estimated to have lead to a reduction in the terrestrial sink by 0.5 PgC yr^{-1} since 1750 (Gitz and Ciais, 2003) but it is neglected here. The models estimate the mean and variability of S_{LAND} based on atmospheric CO_2 and climate, and thus both terms can be compared to the budget residual.

The standard deviation of the annual CO_2 sink across the nine DGVMs ranges from ±0.2 to ±1.3 PgC yr^{-1}, with an average of ±0.7 PgC yr^{-1} for the period 1960 to 2009. This is an improvement from the 0.95 PgC yr^{-1} presented in Le Quéré et al. (2009) using an ensemble of five models. As this standard deviation across the DGVM models and around the mean trends is of the same magnitude as the combined uncertainty due to the other components (E_{FF}, E_{LUC}, G_{ATM}, S_{OCEAN}), the DGVMs do not provide further constrains on the terrestrial CO_2 sink compared to the residual of the budget (Eq. 7). However they confirm that the sum of our knowledge on annual CO_2 emissions and their partitioning is plausible (see Discussion), and they enable the attribution of the fluxes to the underlying processes and provide a breakdown of the regional contributions (not shown here).

3 Results

3.1 Global carbon budget averaged over decades and its variability

The global carbon budget averaged over the last decade (2002–2011) is shown in Fig. 1. For this time period, 89 % of the total emissions ($E_{\mathrm{FF}} + E_{\mathrm{LUC}}$) were caused by fossil fuel combustion and cement production, and 11 % by land-use change. The total emissions were partitioned among the atmosphere (46 %), ocean (27 %) and land (28 %). All components except land-use change emissions have grown since 1959 (Figs. 2 and 3), with important interannual variability in the atmospheric growth rate caused primarily by variability in the land CO_2 sink (Fig. 3), and some decadal variability in all terms (Table 4).

Global CO_2 emissions from fossil fuel combustion and cement production have increased every decade from an average of 3.1 ± 0.2 PgC yr^{-1} in the 1960s to 8.3 ± 0.4 PgC yr^{-1} during 2002–2011 (Table 4). The growth rate in these emissions decreased between the 1960s and the 1990s, from 4.5 % yr^{-1} in the 1960s, 2.9 % yr^{-1} in the 1970s, 1.9 % yr^{-1} in the 1980s, 1.0 % yr^{-1} in the 1990s, and increased again since year 2000 at an average of 3.1 % yr^{-1}. In contrast, CO_2 emissions from LUC have remained constant at around 1.5 ± 0.5 PgC yr^{-1} during 1960–1999, and decreased to 1.0 ± 0.5 PgC yr^{-1} since year 2000. The decreased emissions from LUC since 2000 is also reproduced by the DGVMs (Fig. 5).

The growth rate in atmospheric CO_2 increased from 1.7 ± 0.1 PgC yr^{-1} in the 1960s to 4.3 ± 0.1 PgC yr^{-1} during 2002–2011 with important decadal variations (Table 4). The ocean CO_2 sink increased from 1.2 ± 0.5 PgC yr^{-1} in the 1960s to 2.5 ± 0.5 PgC yr^{-1} during 2002–2011, with decadal variations of the order of a few tenths of PgC yr^{-1}. The low uptake anomaly around year 2000 originates from multiple regions in all models (west Equatorial Pacific, Southern Ocean and North Atlantic), and is caused by climate variability. The land CO_2 sink increased from 1.7 ± 0.8 PgC yr^{-1} in the 1960s to 2.6 ± 0.8 PgC yr^{-1} during 2002–2011, with important decadal variations of 1–2 PgC yr^{-1}. The high uptake anomaly around year 1991 is thought to be caused by the effect of the volcanic eruption of Mount Pinatubo, and is reproduced in some of the models only, but not by the model average (Fig. 5).

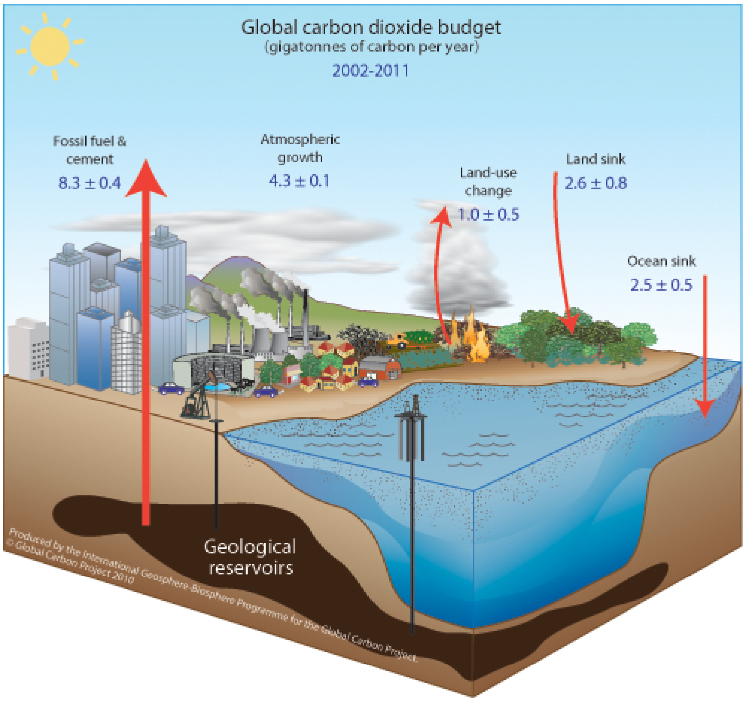

Figure 1. Schematic representation of the overall perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2002–2011. The arrows represent emission from fossil fuel burning and cement production; emissions from deforestation and other land-use change; and the carbon sinks from the atmosphere to the ocean and land reservoirs. The annual growth of carbon dioxide in the atmosphere is also shown. All fluxes are in units of PgC yr^{-1}, with uncertainties reported as ±1 sigma (68 % confidence that the real value lies within the given interval) as described in the text. This Figure is an update of one prepared by the International Geosphere Biosphere Programme for the GCP, first presented in Le Quéré (2009).

3.2 Global carbon budget for year 2011 and emissions projection for 2012

Global CO_2 emissions from fossil fuel combustion and cement production reached 9.5 ± 0.5 PgC in 2011 (Fig. 4; see also Peters et al., 2013). The total emissions in 2011 were distributed among coal (43 %), oil (34 %), gas (18 %), cement (4.9 %) and gas flaring (0.7 %). These first four categories increased by 5.4, 0.7, 2.2, and 2.7 % respectively over the previous year, without enough data to calculate the change for gas flaring. Using Eq. (5), we estimate that global CO_2 emissions in 2012 will reach 9.7 ± 0.5 PgC, or 2.6 % above 2011 levels (likely range of 1.9–3.5; Peters et al., 2013), and that emissions in 2012 will thus be 58 % above emissions in 1990. The expected value is computed using the world GDP projection of 3.3 % made by the IMF (October 2012) and a growth rate for I_{FF} of −0.7 %, which is the average from the previous 10 yr. The uncertainty range is based on 0.2 % for GDP growth (the range in IMF estimates published in January, April, July, and October 2012) and the range in I_{FF} due to short term trends of −0.1 % yr^{-1} (2007–2011) and medium term trends of −1.2 % yr^{-1} (1990–2011); the combined uncertainty range is therefore 1.9 % (3.3–1.2–0.2) and 3.5 % (3.3–0.1 + 0.2). Projections made for the 2009, 2010, and 2011 CO_2 budget compared well to the actual CO_2 emissions for that year (Table 5) and were useful to capture the current state of the fossil fuel emissions.

In 2011, global CO_2 emissions were dominated by emissions from China (28 % in 2011), the USA (16 %), the EU (27 member states; 11 %), and India (7 %). The per-capita CO_2 emissions in 2011 were 1.4 tC $person^{-1}$ yr^{-1} for the globe, and 4.7, 1.8, 2.0 and 0.5 tC $person^{-1}$ yr^{-1} for the USA, China, the EU and India, respectively (Fig. 4e).

Territorial-based emissions in Annex B countries have remained stable from 1990–2000, while consumption-based emissions have grown at 0.5 % yr^{-1} (Fig. 4c). In non-Annex B countries territorial-based emissions have grown at 4.4 % yr^{-1}, while consumption-based emissions have grown at 4.0 % yr^{-1}. In 1990, 65 % of global territorial-based emissions were emitted in Annex B countries, while in 2010 this had reduced to 42 %. In terms of consumption-based emissions this split was 66 % in 1990 and 46 % in 2010. The difference between territorial-based and consumption-based emissions (the net emission transfer via international trade) from non-Annex B to Annex B countries has increased from 0.04 PgC yr^{-1} in 1990 to 0.38 PgC in 2010 (Fig. 4), with an average annual growth rate of 9 % yr^{-1}. The increase in net emission transfers of 0.33 PgC from

Table 5. Actual CO_2 emissions from fossil fuel combustion and cement production (E_{FF}) compared to projections made the previous year based on world GDP and the fossil fuel intensity of GDP (I_{FF}). The "Actual" values and the "Projected" value for 2012 refer to those presented in this paper.

Component	2009[a]		2010[b]		2011[c]		2012
	Projected	Actual	Projected	Actual	Projected	Actual	Projected
E_{FF}	–2.8 %	–0.3 %	> 3 %	5.1 %	3.1 ± 1.5 %	3.1 %	2.6 (1.9–3.5) %
GDP	–1.1 %	0.1 %	4.8 %	5.3 %	4.0 %	3.9 %	3.3 %
I_{FF}	–1.7 %	–0.4 %	>–1.7 %	+0.2 %	–0.9 ± 1.5 %	–0.8 %	–0.7 %

[a] Le Quéré et al. (2009), [b] Friedlingstein et al. (2010), [c] Peters et al. (2013)

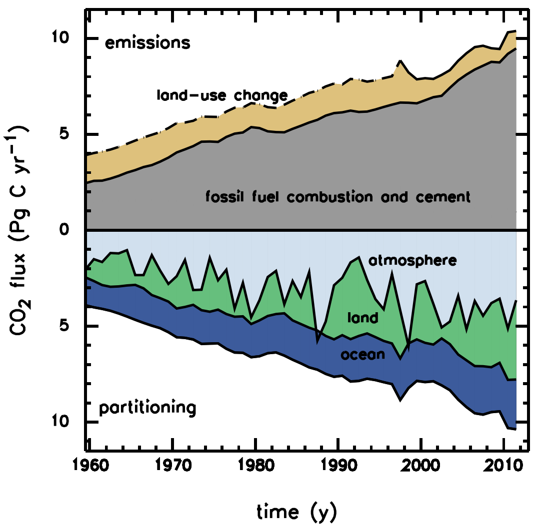

Figure 2. Combined components of the global carbon budget illustrated in Fig. 1 as a function of time, for (top) emissions from fossil fuel combustion and cement production (E_{FF}; grey) and emissions from land-use change (E_{LUC}; brown), and (bottom) their partitioning among the atmosphere (G_{ATM}; light blue), land (S_{LAND}; green) and ocean (S_{OCEAN}; dark blue). All time series are in PgC yr^{-1}. Land-use change emissions include management–climate interactions from year 1997 onwards, where the line changes from dashed to full.

1990–2008 compares with the emission reduction of 0.2 PgC in Annex B countries. These results clearly show a growing net emission transfer via international trade from non-Annex B to Annex B countries. In 2010, the biggest emitters from a territorial-based perspective were China (26 %), USA (17 %), EU (12 %), and India (7 %), while the biggest emitters from a consumption-based perspective were China (22 %), USA (18 %), EU (15 %), and India (6 %).

Global CO_2 emissions from Land-Use Change activities were 0.9 ± 0.5 PgC in 2011, with the decrease of 0.2 PgC yr^{-1} from the year 2010 estimate based on satellite-detected fire activity.

Atmospheric CO_2 growth rate was 3.6 ± 0.2 PgC in 2011 (1.69 ± 0.09 ppm; Fig. 3). This is slightly below the 2000–2009 average of 4.0 ± 0.1 PgC yr^{-1}, though the interannual variability in atmospheric growth rate is large.

The ocean CO_2 sink was 2.7 ± 0.5 PgC yr^{-1} in 2011, a slight increase compared to the sink of 2.5 ± 0.5 PgC yr^{-1} in 2010 and 2.4 ± 0.5 PgC yr^{-1} in 2000–2009 (Fig. 3). All models suggest that the ocean CO_2 sink in 2011 was greater than the 2010 sink.

The terrestrial CO_2 sink calculated as the residual from the carbon budget was 4.1 ± 0.9 PgC in 2011, well above the 2.7 ± 0.9 PgC in 2010 and 2.4 ± 0.9 PgC yr^{-1} in 2000–2009 (Fig. 3). This large sink is consistent with enhanced CO_2 sink during the wet and cold conditions associated with the strong La Niña condition that started in the middle of 2010 and ended in March 2012, as discussed for previous events (Keeling et al., 1995; Peylin et al., 2005). Results from DGVMs are available to year 2010 only (Fig. 5).

4 Discussion

Each year when the global carbon budget is published, each component for all previous years is updated to take into account corrections that are due to further scrutiny and verification of the underlying data in the primary input datasets (Fig. 6). The updates have generally been relatively small and generally focused on the most recent past years, except for LUC between 2008 and 2009 when LUC emissions were revised downwards by 0.56 PgC yr^{-1}, and after 1997 for this budget where we introduced an estimate of interannual variability from management–climate interactions. The 2008/2009 revision was the result of the release of FAO 2010, which contained a major update to forest cover change for the period 2000–2005 and provided the data for the following 5 yr to 2010. Updates were at most 0.24 PgC yr^{-1} for the fossil fuel and cement emissions, 0.19 PgC yr^{-1} for the atmospheric growth rate, 0.20 PgC yr^{-1} for the ocean CO_2 sink. The update for the residual land CO_2 sink was also large, with maximum value of 0.71 PgC yr^{-1}, directly reflecting the revision in other terms of the budget. Likewise, the land sink estimated by DGVMs has also reflected the increasing availability of model output to do these calculations.

Our capacity to separate the CO_2 budget components can be evaluated by comparing the land CO_2 sink estimated with

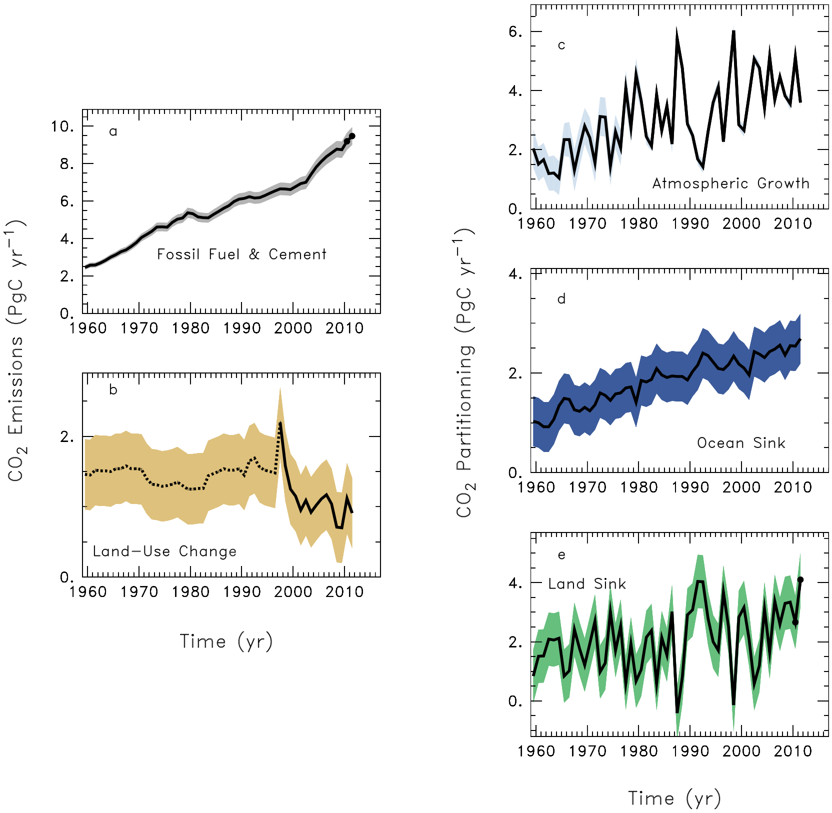

Figure 3. Components of the global carbon budget and their uncertainties as a function of time, presented individually for **(a)** emissions from fossil fuel combustion and cement production (E_{FF}), **(b)** emissions from land-use change (E_{LUC}) with management–climate interactions based on fire activities in deforested areas (full line) or not (dashed line), **(c)** atmospheric CO_2 growth rate (G_{ATM}), **(d)** the ocean CO_2 sink (S_{OCEAN}, positive indicates a flux from the atmosphere to the ocean), and **(e)** the land CO_2 sink (S_{LAND}, positive indicates a flux from the atmosphere to the land). All time series are in PgC yr^{-1} with the uncertainty bounds representing ±1 sigma in shaded colour. The black dots in panels **(a)** and **(e)** show the values based on emissions extrapolated using BP energy statistics.

the budget residual (S_{LAND}), which includes errors and biases from all components, with the land CO_2 sink estimates by the DGVM ensemble, which are based on our understanding of processes of how the land responds to increasing CO_2 and climate change and variability. The two estimates are generally close (Fig. 5), both for the mean and for the interannual variability. The DGVMs correlate with the budget residual with $r = 0.34$ to 0.45 (median of $r = 0.43$), and $r = 0.48$ for the model mean (Fig. 5). The DGVMs produce a decadal mean and standard deviation across nine models of 2.6 ± 1.0 PgC yr^{-1} for the period 2000–2009, nearly the same as the estimate produced with the budget residual (Table 4). Analysis of regional CO_2 budgets would provide further information to quantify and improve our estimates, as has been undertaken by the REgional Carbon Cycle Assessment and Processes (RECCAP) exercise (Canadell et al., 2011).

Annual estimations of each component of the global carbon budgets have their limitations, some of which could be improved with better data and/or a better understanding of carbon dynamics. The primary limitations involve resolving fluxes on annual timescales and providing updated estimates for recent years for which data-based estimates are not yet available. Of the various terms in the global budget, only the fossil-fuel burning and atmospheric growth rate terms are based primarily on empirical inputs with annual resolution. The data on fossil fuel consumption and cement production are based on survey data in all countries. The other terms can be provided on an annual basis only through the use of models. While these models represent the current state of the art, they provide only estimates of actual changes. For example, the decadal trends in ocean uptake and the interannual variations associated with El Niño/La Niña (ENSO) are not directly constrained by observations, although many of the processes controlling these trends are sufficiently well known that the model-based trends still have value as benchmarks for further validation. Land-use emissions estimates and their variations from year to year have even larger uncertainty, and much of the underlying data are not available as an annual update. Efforts are underway to work with annually available satellite area change data or FAO reported data in combination with fire data and modelling to provide annual updates for future budgets. The best resolved changes are

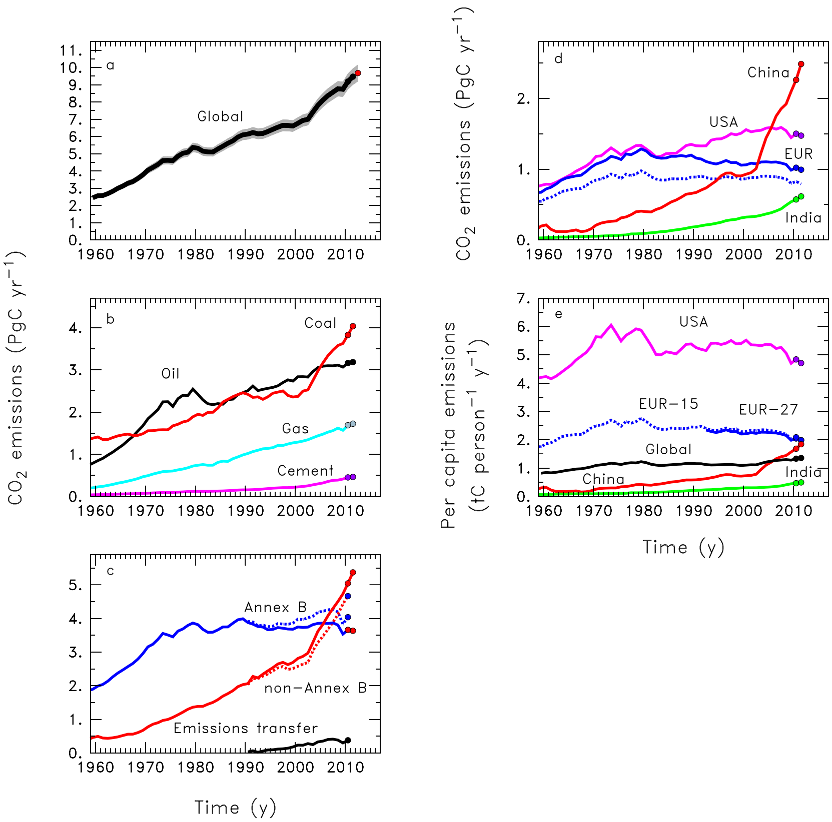

Figure 4. CO_2 emissions from fossil fuel combustion and cement production for **(a)** the globe, including an uncertainty of ±5 % (grey shading), the emissions extrapolated using BP energy statistics (black dots) and the emissions projection for year 2012 based on GDP projection (red dot), **(b)** global emissions by fuel type, including coal (red), oil (black), gas (light blue), and cement (purple), and excluding gas flaring which is small (0.7 % in 2011), **(c)** territorial (full line) and consumption (dashed line) emissions for the countries listed in the Annex B of the Kyoto Protocol (blue lines; mostly advanced economies with emissions limitations) versus non-Annex B countries (red lines), also shown are the emissions transfer from non-Annex B to Annex B countries (black line) **(d)** territorial CO_2 emissions for the top three country emitters (USA – purple; China – red; India – green) and for the European Union (EU; full blue for the 27 states members of the EU in 2011; dash blue for the 15 states members of the EU in 1997 when the Kyoto Protocol was signed), and **(e)** per-capita emissions for the top three country emitters and the EU (all colours as in panel **d**). In panels **(b)** to **(e)**, the dots show the years where the emissions were extrapolated using BP energy statistics. All time series are in PgC yr^{-1} except the per-capita emissions (panel **e**), which are in tonnes of carbon per person per year.

in atmospheric growth (G_{ATM}), fossil-fuel emissions (E_{FF}), and by difference, the change in the sum of the remaining terms ($S_{OCEAN} + S_{LAND} - E_{LUC}$). The variations from year to year in these remaining terms are largely model-based at this time. Further efforts to increase the availability and use of annual data for estimating the remaining terms with annual to decadal resolution are especially needed.

Our approach also depends on the reliability of the energy and land cover change statistics provided at the country level, and are thus potentially subject to biases. Thus it is critical to develop multiple ways to estimate the carbon balance at the global and regional level, including from the inversion of atmospheric CO_2 concentration, the use of other oceanic and atmospheric tracers, and the compilation of emissions using alternative statistics (e.g. sectors). Multiple approaches going from global to regional would greatly help improve confidence and reduce uncertainty in CO_2 emissions and their fate.

5 Conclusions

The estimation of global CO_2 emissions and sinks is a major effort by the carbon cycle research community that requires a combination of measurements and compilation of statistical estimates and results from models. The delivery of an annual CO_2 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 datasets associated with the annual CO_2 budget, including scientists, policy makers, businesses, journalists, and the broader civil society increasingly engaged in the climate

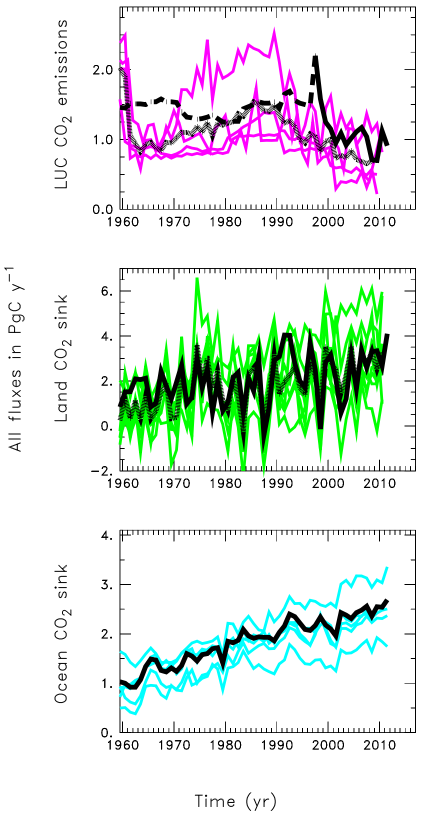

Figure 5. Comparison of (top panel) CO_2 emissions from land-use change (LUC), (middle panel) land CO_2 sink (S_{LAND}), and (bottom panel) ocean CO_2 sink (S_{OCEAN}) between the CO_2 budget values estimated here (black line), and those estimated from process models without any normalisation to observations (Table 3; coloured lines). The thin dotted black lines in the top and middle panels are the model averages. The LUC emissions from the CO_2 budget estimate is dashed before year 1997 to highlight the start of the satellite data from that year, as used to quantify the interannual variability from management–climate interactions based on fire activities in deforested areas.

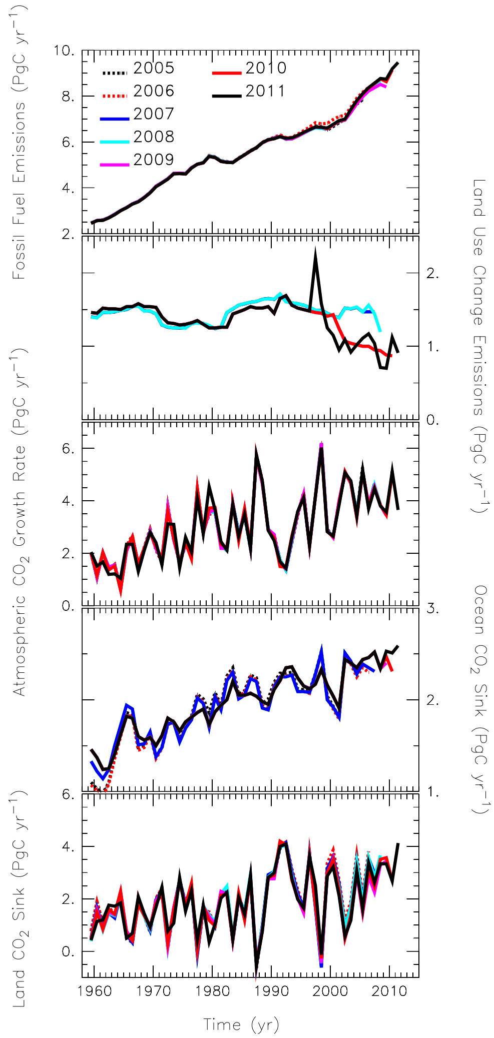

Figure 6. Comparison of global carbon budget components released annually by GCP since 2005. CO_2 emissions from both **(a)** fossil fuel combustion and cement production, and **(b)** land-use change, and their partitioning among **(c)** the atmosphere, **(d)** the ocean, and **(e)** the land. The different curves were published in (dashed black) Raupach et al. (2007), (dashed red) Canadell et al. (2007), (dark blue) online only, (light blue) Le Quéré et al. (2009), (pink) Friedlingstein et al. (2010), (red) Peters et al. (2012a), and (black) this study. All values are in PgC yr^{-1}.

change debate. Second, over the last decade we have seen important changes in the human and biophysical worlds (e.g. increase in fossil fuel emissions growth, sea and air warming, snow and ice melt), which require a more frequent assessment of what we can learn regarding future dynamics and the needs for climate change mitigation. In very general terms, both the ocean and the land surface presently mitigate a large fraction of anthropogenic emissions. Any significant change in this situation is of great importance to climate policymaking, as it implies different emissions levels to achieve warming target aspirations such as remaining below the two-degrees of global warming since pre-industrial periods. Better constraints of carbon cycle models against the contemporary datasets raises the hope that they will be more accurate at future projections.

This all requires more frequent, robust, and transparent datasets and methods that can be scrutinized and replicated. After seven annual releases done by the GCP, the effort is growing and the traceability of the methods has become increasingly complex. Here, we have documented in detail the datasets and methods used to compile the annual updates of the global carbon budget, explained the rationale for the choices made, the limitations of the information, and finally highlighted need for additional information where gaps exist.

This paper, via "living reviews", will help to keep track of new budget updates. The evolution over time of the CO_2

budget is now a key indicator of the anthropogenic perturbation of the climate system and its annual delivery joins a set of climate indicators to monitor the evolution of human-induced climate change, such as the annual updates on the global surface temperature, sea level rise, minimum Arctic sea ice extent and others.

6 Data access

The accompanying database includes one excel file organised in seven spreadsheets:

1. The global carbon budget (1959–2011).
2. Global CO_2 emissions from fossil fuel combustion and cement production by fuel type, and the per-capita emissions (1959–2011).
3. Territorial-based (e.g. as reported to the UN Framework Convention on Climate Change) country CO_2 emissions from fossil fuel combustion and cement production (1959–2011).
4. Consumption-based country CO_2 emissions from fossil fuel combustion and cement production and emissions transfer from the international trade of goods and services (1990–2010).
5. CO_2 emissions from land-use change from the individual methods and models (1959–2011).
6. Ocean CO_2 sink from the individual ocean models (1959–2011).
7. Terrestrial residual CO_2 sink from the DGVMs (1959–2010).

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