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# The global carbon budget 1959–2011

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## Abstract

Accurate assessment 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. Based on energy statistics, we estimate that the global emissions of $CO_2$ from fossil fuel combustion and cement production were $9.5 \pm 0.5\,\mathrm{PgC\,yr^{-1}}$ in 2011, 3.0 percent above 2010 levels. We project these emissions will increase 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. Global net $CO_2$ emissions from Land-Use Change, including deforestation, are more difficult to update annually because of data availability, but combined evidence from land cover change data, fire activity in regions undergoing deforestation and models suggests those net emissions were $0.9 \pm 0.5\,\mathrm{PgC\,yr^{-1}}$ in 2011. The global atmospheric $CO_2$ concentration is measured directly and reached $391.38 \pm 0.13$ ppm at the end of year 2011, increasing $1.70 \pm 0.09\,\mathrm{ppm\,yr^{-1}}$ or $3.6 \pm 0.2\,\mathrm{PgC\,yr^{-1}}$ in 2011. Estimates from four ocean models suggest that the ocean $CO_2$ sink was $2.6 \pm 0.5\,\mathrm{PgC\,yr^{-1}}$ in 2011, implying a global residual terrestrial $CO_2$ sink of $4.1 \pm 0.9\,\mathrm{PgC\,yr^{-1}}$. All uncertainties are reported as ±1 sigma (68 % confidence assuming Gaussian error distributions that the real value lies within the given interval), 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 carbon data presented here can be downloaded from the Carbon Dioxide Information Analysis Center (doi:10.3334/CDIAC/GCP_V2012).

## 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 391.4 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 Revolution 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 time scales 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 direct and indirect *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 and other anthropogenic 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; $E_{\mathrm{LUC}}$), (3) the growth rate of $CO_2$ in the atmosphere ($G_{\mathrm{ATM}}$), and (4) the uptake of $CO_2$ by the "$CO_2$ sinks" in the ocean ($S_{\mathrm{OCEAN}}$) and on land ($S_{\mathrm{LAND}}$). The $CO_2$ sinks as defined here include the response of the land and oceans 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:

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

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 is the anthropogenic perturbations to inland freshwaters, estuaries, and coastal areas carbon cycling, that modify both lateral fluxes transported from land ecosystems to the open ocean, and "vertical" $CO_2$ fluxes of rivers and estuaries outgassing, and the air-sea $CO_2$ net exchange of coastal areas (Battin et al., 2008; Aufdenkampe et al., 2011). These flows are omitted in absence of details on the natural versus anthropogenic terms of these loops of the carbon cycle. The inclusion of these fluxes of anthropogenic $CO_2$ would affect the estimates of $S_{\mathrm{LAND}}$ and perhaps $S_{\mathrm{OCEAN}}$ in Eq. (1), but not $G_{\mathrm{ATM}}$.

The global carbon 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 $CO_2$ budgets for year 2005 (Raupach et al., 2007; including fossil emissions only), year 2006 (Canadell et al., 2007), year 2007 (published online), year 2008 (Le Quéré et al., 2009), year 2009

(Friedlingstein et al., 2010), and most recently, year 2010 (Peters et al., 2012b). 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 improvements 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 only "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 $CO_2$ budget and associated uncertainties for the period 1959–2011. It presents the global $CO_2$ 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 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 (and their uncertainty); this makes the dataset a unique resource for research of the carbon cycle during the fossil fuel era. For this paper, we use CDIAC emissions data up to period 1959–2009, and preliminary estimates based on the BP annual energy review for 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. The preliminary estimates are replaced by the more complete CDIAC data when available. Past experience shows that projections based on the BP data 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 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 are 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, because of 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).

### 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. Davies et al., 2011) 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 (Peters et al., 2011a) 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 (Peters et al., 2012b). 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., 2011b).

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.

The consumption-based emission inventories in this carbon budget have several improvements over previous years. 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 Netherlands in 2008 and 2009, and for these two countries, the trade shares for 2008–2010 are based on the 2007 trade shares.

This data does 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 unharmonised 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 $E_{\mathrm{FF}}$ is decomposed by the product of GDP and the fossil fuel carbon intensity of the economy ($I_{\mathrm{FF}}$) 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 $I_{\mathrm{FF}}$ 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 Eq. (4) by Eq. (2) gives:

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

where the left hand term is the relative growth rate of $E_{\mathrm{FF}}$, and the right hand terms are the relative growth rates of GDP and $I_{\mathrm{FF}}$, 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 $I_{\mathrm{FF}}$ 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: $[(E_{FF}(t_0+1) - E_{FF}(t_0))/E_{FF}(t_0)] \cdot 100$. 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:

$$\frac{1}{E_{FF}}\frac{dE_{FF}}{dt} = \frac{d(\ln E_{FF})}{dt} \quad (6)$$

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. (6). This method differs from previous papers (Raupach et al., 2007; 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 ($< 0.05\,\%$) 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 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 also use independent estimates from Dynamic Global Vegetation Models (Sect. 2.2.3) to help quantifying 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 fuel-wood 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 data set is non-spatial and aggregated by regions. The carbon stocks on land (biomass and soils), and their response 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.

### 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 $E_{\text{LUC}}$ 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 $E_{\text{LUC}}$ 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 on 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 $E_{\text{LUC}}$.

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 $E_{\text{LUC}}$. We calculate the anomaly in these emissions over the 1997–2011 time period, and add this to average $E_{\text{LUC}}$ 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 $S_{\text{LAND}}$.

### 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 provide exactly $E_{LUC}$ 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 area (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 data set 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 data set, 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., 2012; Kato et al., 2012; Poulter et al., 2010; Stocker et al., 2011b; Table 3). While many published DGVM LUC emissions estimates exist, these model runs were driven by a consistent updated HYDE LUC data set 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 $\mathrm{PgC\,yr^{-1}}$, with an average of 0.42 $\mathrm{PgC\,yr^{-1}}$ from 1960 to 2009. One of the four models (Jain et al., 2012) was used with three different LUC data sets (including HYDE and FAO FRA, 2005) (Jain et al., 2012; Meiyappan and Jain, 2012). The standard deviation for decadal means in these three model runs was ±0.19 $\mathrm{PgC\,yr^{-1}}$ for 1990 to 2005, and ranged from 0.06 to 0.70 $\mathrm{PgC\,yr^{-1}}$ for annual estimates with an average of ±0.27 $\mathrm{PgC\,yr^{-1}}$ 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 $\mathrm{PgC\,yr^{-1}}$) and the standard deviation due to different land cover change data sets (0.27 $\mathrm{PgC\,yr^{-1}}$) we get a combined standard deviation of 0.5 $\mathrm{PgC\,yr^{-1}}$.

We use the combined standard deviation ±0.5 $\mathrm{PgC\,yr^{-1}}$ 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 ±0.5 $\mathrm{PgC\,yr^{-1}}$ is slightly lower than that of ±0.7 $\mathrm{PgC\,yr^{-1}}$ 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 ±0.5 $\mathrm{PgC\,yr^{-1}}$ (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 ±0.5 $\mathrm{PgC\,yr^{-1}}$ here for the decadal averages presented Table 4.

## 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) and other research groups. 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 November–February months (for Mauna Loa) and December–January months (for the globe) 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 time scales. 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 Meteorological Organization World Data Center for Greenhouse Gases, NOAA/ESRL, 2012) for the

start and end points (the decadal change uncertainty is the $\mathrm{sqrt}(2 \cdot (0.35\,\mathrm{ppm})^2)/10\,\mathrm{yr}$ assuming that each yearly measurement error is independent). This uncertainty is also used in Table 4.

### 2.3.2 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 (omitted in Eq. 1) arise through anthropogenic emissions of fugitive fossil fuel $CH_4$ and CO, and changes in oxidation rates, e.g. in response to climate variability. 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 time-scale (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., 2012). 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., 2012), 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. 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; Manning and Keeling, 2006; McNeil et al., 2003) (Table 1). Here we adopt this mean $CO_2$ sink, and compute the trends in the ocean $CO_2$ sink for 1959–2011 using a combination of global ocean biogeochemistry models. 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.

For 1959–2008, four model estimates were used (Le Quéré et al., 2009). For years 2009 to 2011, we use the interannual variability estimated by the models available to us. These include updates of three of the models used in Le Quéré et al. (2009); Aumont and Bopp (2006); Doney et al. (2009); Buitenhuis et al. (2010) and one further model estimate updated from Assman et al. (2010). We do not recompute the 1959–2008 trend to avoid introducing annual changes in the trend that are associated with the model ensemble rather than with real progress in knowledge or in the number of models available. Instead, we compute the average model anomaly compared to the average of 1999–2008, the ten-year period immediately preceding the end of the trend previously estimated and add this to the estimate presented in Le Quéré et al. (2009). The standard deviation of the ocean model ensemble is generally about 0.1–0.2 PgC $yr^{-1}$. We estimate that the uncertainty in the annual ocean $CO_2$ sink is about ±0.5 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. This terrestrial sink was often referred as the "missing sink" prior to the 1990s, before atmospheric $CO_2$ (Tans et al., 1990), $\delta^{13}C$ (Quay et al., 1992) and $O_2$ (Keeling et al., 1996) studies independently constrained the ocean and hence the land sinks.

#### 2.5.1 Residual of the budget

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

$$S_{LAND} = E_{FF} + E_{LUC} - (G_{ATM} + S_{OCEAN}) \tag{7}$$

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 component of Eq. (7).

#### 2.5.2 DGVMs

A comparison of the residual calculation of $S_{LAND}$ in Eq. (7) 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)" (Sitch et al., 2012) (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 ±0.8 to ± 1.8 $PgC\,yr^{-1}$, with an average of ±1.1 $PgC\,yr^{-1}$ for the period 1960 to 2009. When only the interannual variability is analysed as in Le Quéré et al. (2009) by removing the mean sink of the 1990s from each estimate individually, the standard deviation of the annual $CO_2$ sink decreases to 0.80 $PgC\,yr^{-1}$, 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 (1) they confirm that the sum of our knowledge on annual $CO_2$ emissions and their partitioning is plausible, (2) they suggest that the uncertainty of ±0.8 $PgC\,yr^{-1}$ for $S_{LAND}$ estimated from Eq. (7)

is an appropriate reflection of current knowledge, and (3) 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 $CO_2$ budget averaged over decades

The global $CO_2$ budget averaged over the last decade (2002–2011) is shown in Fig. 1. For this time period, 89 % of the total emissions ($E_{FF} + E_{LUC}$) 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 and 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 $3.1 \pm 0.2\,\mathrm{PgC\,yr^{-1}}$ in the 1960s to $8.3 \pm 0.4\,\mathrm{PgC\,yr^{-1}}$ during 2002–2011 (Table 4). The growth rate in these emissions decreased between the 1960s and the 1990s, from $4.5\,\%\,\mathrm{yr^{-1}}$ in the 1960s, $2.9\,\%\,\mathrm{yr^{-1}}$ in the 1970s, $1.9\,\%\,\mathrm{yr^{-1}}$ in the 1980s, $1.0\,\%\,\mathrm{yr^{-1}}$ in the 1990s, and increased again since year 2000 at an average of $3.1\,\%\,\mathrm{yr^{-1}}$. In contrast, $CO_2$ emissions from LUC have remained constant at around $1.5 \pm 0.5\,\mathrm{PgC\,yr^{-1}}$ during 1960–1999, and decreased to $1.0 \pm 0.5\,\mathrm{PgC\,yr^{-1}}$ 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 $1.7 \pm 0.1\,\mathrm{PgC\,yr^{-1}}$ in the 1960s to $4.3 \pm 0.1\,\mathrm{PgC\,yr^{-1}}$ during 2002—2011 with important decadal variations (Table 4). The ocean $CO_2$ sink increased from $1.5 \pm 0.5\,\mathrm{PgC\,yr^{-1}}$ in the 1960s to $2.5 \pm 0.5\,\mathrm{PgC\,yr^{-1}}$ during 2002–2011, while the land $CO_2$ sink increased from

$1.3 \pm 0.8\,\mathrm{PgC\,yr^{-1}}$ in the 1960s to $2.6 \pm 0.8\,\mathrm{PgC\,yr^{-1}}$ during 2002–2011, also with important decadal variations.

### 3.2 Global $CO_2$ budget for year 2011 and emissions projection for 2012

Global $CO_2$ emissions from fossil fuel combustion and cement production reached $9.5 \pm 0.5$ PgC in 2011 (Fig. 4; see also Peters et al., 2012a). 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 $9.7 \pm 0.5$ PgC, or 2.6 % above 2011 levels (likely range of 1.9–3.5, Peters et al., 2012a), 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 $-0.1\,\%\,\mathrm{yr^{-1}}$ (2007–2011) and medium term trends of $-1.2\,\%\,\mathrm{yr^{-1}}$ (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 $1.4\,\mathrm{tC\,person^{-1}\,yr^{-1}}$ for the globe, and 4.7, 2.0, 1.8, and $0.5\,\mathrm{tC\,person^{-1}\,yr^{-1}}$ 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 $0.5\,\%\,\mathrm{yr^{-1}}$ (Fig. 4c). In non-Annex B countries territorial-based emissions have grown at $4.4\,\%\,\mathrm{yr^{-1}}$, 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 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 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 (1.70 ± 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 2.6 ± 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 2.3 ± 0.5 PgC $yr^{-1}$ in 2000–2009 (Fig. 3). All four 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 (Peylin et al., 2005; Tian et al., 1998). Results from DGVMs are available to year 2010 only (Fig. 5).

## 4 Discussion

Each year when the global $CO_2$ 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 data sets (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 the budget residual ($S_{\mathrm{LAND}}$), 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 ± 0.8 PgC $yr^{-1}$, 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 $CO_2$ 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 time scales 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 Niño (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 in atmospheric growth ($G_{\text{ATM}}$), fossil-fuel emissions ($E_{\text{FF}}$), and by difference, the change in the sum of the remaining terms ($S_{\text{OCEAN}} + S_{\text{LAND}} - E_{\text{LUC}}$). 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 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 datasets associated with the annual $CO_2$ budget including scientists, policy makers, businesses, journalists, and the broader civil society increasingly engaged in the climate change debate. Second, over the last decade we have seen rapid changes in the human and biophysical worlds (e.g. acceleration of fossil fuel emissions and the response of land and ocean carbon sinks to global climate phenomena), 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 oceans 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 projection.

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 carbon 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 (1959–2011).

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## References

Ahlström, A., Miller, P. A., and Smith, B.: Too early to infer a global NPP decline since 2000, Geophys. Res. Lett., 39, L15403, doi:10.1029/2012GL052336, 2012.

Andres, R. J., Boden, T. A., Bréon, F.-M., Ciais, P., Davis, S., Erickson, D., Gregg, J. S., Jacobson, A., Marland, G., Miller, J., Oda, T., Olivier, J. G. J., Raupach, M. R., Rayner, P., and Treanton, K.: A synthesis of carbon dioxide emissions from fossil-fuel combustion, Biogeosciences, 9, 1845–1871, doi:10.5194/bg-9-1845-2012, 2012.

Archer, D., Eby, M., Brovkin, V., Ridgwell, A., Cao, L., Mikolajewicz, U., Caldeira, K. M., K., Munhoven, G., Montenegro, A., and Tokos, K.: Atmospheric Lifetime of Fossil Fuel Carbon Dioxide, Annu. Rev. Earth Pl. Sc., 37, 117–134, 2009.

Assmann, K. M., Bentsen, M., Segschneider, J., and Heinze, C.: An isopycnic ocean carbon cycle model, Geosci. Model Dev., 3, 143–167, doi:10.5194/gmd-3-143-2010, 2010.

Aufdenkampe, A. K., Mayorga, E., Raymond, P. A., Melack, J. M., Doney, S. C., Alin, S. R., Aalto, R. E., and Yoo, K.: Riverine coupling of biogeochemical cycles between land, oceans and atmosphere, Frontiers Ecology Environ., 9, 53–60, 2011.

Aumont, O. and Bopp, L.: Globalizing results from ocean in situ iron fertilization studies, Global Biogeochem. Cy., 20, GB2017, doi:10.1029/2005GB002591, 2006.

Baccini, A., Goetz, S. J., Walker, W. S., Laporte, N. T., Sun, M., Sulla-Menashe, D., Hackler, J., Beck, P. S. A., Dubayah, R., Friedl, M. A., Samanta, S., and Houghton, R. A.: Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps, Nature Clim. Change, 2, 182–186, 2012.

Ballantyne, A. P., Alden, C. B., Miller, J. B., Tans, P. P., and White, J. W. C.: Increase in observed net carbon dioxide uptake by land and oceans during the last 50 years, Nature, 488, 70–72, 2012.

Ballhorn, U., Siegert, F., Mason, M., and Limin, S.: Derivation of burn scar depths and estimation of carbon emissions with LIDAR in Indonesian peatlands, P. Natl. Acad. Sci., 106, 21213–21218, doi:10.1073/pnas.0906457106, 2009.

Battin, T. J., Kaplan, L. A., Findlay, S., Hopkinson, C. S., Marti, E., Packman, A. I., Newbold, J. D., and Sabater, F.: Biophysical controls on organic carbon fluxes in fluvial networks, Nat. Geosci., 1, 95–100, 2008.

Statistical Review of World Energy 2012: http://www.bp.com/sectionbodycopy.do?categoryId=7500&contentId=7068481, last access: October 2012.

Buitenhuis, E. T., Rivkin, R. B., Sailley, S., and Le Quéré, C.: Biogeochemical fluxes through microzooplankton, Global Biogeochem. Cy., 24, Gb4015, doi:10.1029/2009gb003601, 2010.

Canadell, J. G., Le Quéré, C., Raupach, M. R., Field, C. B., Buitenhuis, E. T., Ciais, P., Conway, T. J., Gillett, N. P., Houghton, R. A., and Marland, G.: Contributions to accelerating atmospheric $CO_2$ growth from economic activity, carbon intensity, and efficiency of natural sinks, P. Natl. Acad. Sci. USA, 104, 18866–18870, doi:10.1073/pnas.0702737104, 2007.

Canadell, J. G., Ciais, P., Gurney, K., Le Quéré, C., Piao, S., Raupach, M. R., and Sabine, C. L.: An international effort to quantify regional carbon fluxes, EOS, 92, 81–82, 2011.

Clark, D. B., Mercado, L. M., Sitch, S., Jones, C. D., Gedney, N., Best, M. J., Pryor, M., Rooney, G. G., Essery, R. L. H., Blyth, E., Boucher, O., Harding, R. J., Huntingford, C., and Cox, P. M.: The Joint UK Land Environment Simulator (JULES), model description – Part 2: Carbon fluxes and vegetation dynamics, Geosci. Model Dev., 4, 701–722, doi:10.5194/gmd-4-701-2011, 2011.

Conway, T. J. and Tans, P. P.: Trends in atmospheric carbon dioxide: http://www.esrl.noaa.gov/gmd/ccgg/trends, last access: 16 November 2012.

Cox, P. M.: Description of the "TRIFFID" dynamic global vegetation model, Hadley Centre, Technical Note 24, 2001.

Davis, S. J., Peters, G. P., and Caldeira, K.: The supply chain of $CO_2$ emissions, P. Natl. Acad. Sci. USA, 108, 18554–18559, 2011.

Denman, K. L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P. M., Dickinson, R. E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., Leite da Silva Dias, P., Wofsy, S. C., and Zhang, X.: Couplings Between Changes in the Climate System and Biogeochemistry, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Doney, S. C., Lima, I., Feely, R. A., Glover, D. M., Lindsay, K., Mahowald, N., Moore, J. K., and Wanninkhof, R.: Mechanisms governing interannual variability in upper-ocean inorganic carbon system and air-sea $CO_2$ fluxes: Physical climate and atmospheric dust, Deep-Sea Res. Pt. II, 56, 640–655, 2009.

Earles, J. M., Yeh, S., and Skog, K. E.: Timing of carbon emissions from global forest clearance, Nature Climate Change, 2, 682–685, 2012.

Enting, I. G., Wigley, T. M. L., and Heimann, M.: Future emissions and concentrations of carbon dioxide: Key ocean/atmosphere/land analyses, Melbourne, 1994.

Falkowski, P., Scholes, R. J., Boyle, E., Canadell, J. G., Canfield, D., Elser, J., Gruber, N., Hibbard, K., Högberg, P., Linder, S., Mackenzie, F. T., Moore III, B., Pedersen, T., Rosenthal, Y., Seitzinger, S., Smetacek, V., and Steffen, W.: The Global Carbon Cycle: A Test of Our Knowledge of Earth as a System, Science, 290, 291–296, 2000.

FAO: Global Forest Resource Assessment 2010, 378 pp., 2010.

Food and Agriculture Organization Statistics Division: http://faostat.fao.org/, 2010.

Friedlingstein, P., Houghton, R. A., Marland, G., Hackler, J., Boden, T. A., Conway, T. J., Canadell, J. G., Raupach, M. R., Ciais, P., and Le Quéré, C.: Update on $CO_2$ emissions, Nat. Geosci., 3, 811–812, doi:10.1038/ngeo1022, 2010.

Giglio, L., Randerson, J. T., van der Werf, G. R., Kasibhatla, P. S., Collatz, G. J., Morton, D. C., and DeFries, R. S.: Assessing variability and long-term trends in burned area by merging multiple satellite fire products, Biogeosciences, 7, 1171–1186, doi:10.5194/bg-7-1171-2010, 2010.

Gitz, V. and Ciais, P.: Amplifying effects of land-use change on future atmospheric $CO_2$ levels, Global Biogeochem. Cy., 17, 1024, doi:10.1029/2002GB001963, 2003.

Goldewijk, K. K., Beusen, A., van Drecht, G., and de Vos, M.: The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years, Global Ecol. Biogeogr., 20, 73–86, 2011.

Gregg, J. S., Andres, R. J., and Marland, G.: China: Emissions pattern of the world leader in $CO_2$ emissions from fossil fuel consumption and cement production, Geophys. Res. Lett., 35, L08806, doi:10.1029/2007gl032887, 2008.

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

Houghton, R. A.: Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000, Tellus B, 55, 378–390, doi:10.1034/j.1600-0889.2003.01450.x, 2003.

Houghton, R. A., van der Werf, G. R., DeFries, R. S., Hansen, M. C., House, J. I., Le Quéré, C., Pongratz, J., and Ramankutty, N.: Chapter G2 Carbon emissions from land use and land-cover change, Biogeosciences Discuss., 9, 835–878, doi:10.5194/bgd-9-835-2012, 2012.

Hurtt, G. C., Chini, L. P., Frolking, S., Betts, R. A., Feddema, J., Fischer, G., Fisk, J. P., Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D. P., and Wang, Y. P.: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, Climatic Change, 109, 117–161, 2011.

Jain, A. K., Meiyappan, P., Song, Y., and House, J. I.: Estimates of carbon emissions from historical land-use and land-cover change, Glob. Change Biol., revised, 2012.

Kato, E., Kinoshita, T., Ito, A., Kamamiya, M., and Yamagata, Y.: Evaluation of spatially explicit emission scenario of land-use change and biomass burning using a process-based biogeochemical model, Journal of Land Use Science, doi:10.1080/1747423X.2011.628705, in press, 2012.

Keeling, C. D., Bacastow, R. B., Bainbridge, A. E., Ekdhal, C. A., Guenther, P. R., and Waterman, L. S.: Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii, Tellus, 28, 538–551, 1976.

Keeling, R. F., Piper, S. C., and Heimann, M.: Global and hemispheric $CO_2$ sinks deduced from changes in atmospheric $O_2$ concentration, Nature, 381, 218–222, 1996.

Kirschke, S., Bousquet, P., Ciais, P., Saunois, M., Dlugokencky, E. J., Bergamaschi, P., Bergmann, D., Blake, D. R., Bruhwiler, L., Cameron-Smith, P., Canadell, J. G., Castaldi, S.,

Chevallier, F., Feng, L., Fraser, A., Fraser, P. J., Heimann, M., Hodson, E. L., Houweling, S., Josse, B., Krummel, P. B., Lamarque, J.-F., Le Quéré, C., Montzka, S. A., Naik, V., O'Doherty, S., Palmer, P. I., Pison, I., Plummer, D., Poulter, B., Prinn, R. G., Rigby, M., Ringeval, B., Santini, M., Schmidt, M., Shindell, D. T., Simpson, I. J., Spahni, R., Steele, L. P., Strode, S. A., Sudo, K., Szopa, S., van der Werf, G. R., Voulgarakis, A., van Weele, M., Weiss, R. F., Williams, J. E., and Zeng, G.: Three decades of methane sources and sinks: budgets and variations, Nat. Geosci., in review, 2012.

Krinner, G., Viovy, N., de Noblet-Ducoudre, N., Ogee, J., Polcher, J., Friedlingstein, P., Ciais, P., Sitch, S., and Prentice, I. C.: A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biogeochem. Cy., 19, Gb1015, doi:10.1029/2003gb002199, 2005.

Lawrence, D. M., Oleson, K. W., Flanner, M. G., Thornton, P. E., Swenson, S. C., Lawrence, P. J., Zeng, X., Yang, Z.-L., Levis, S., Sakaguchi, K., Bonan, G. B., and Slater, A. G.: Parameterization improvements and functional and structural advances in version 4 of the Community Land Model, Journal of Advances in Modeling Earth Systems, 3, M03001, doi:10.1029/2012MS000165, 2011.

Le Quéré, C.: Closing the global budget for $CO_2$, Glob. Change, 74, 28–31, 2009.

Le Quéré, C., Rödenbeck, C., Buitenhuis, E. T., Conway, T. J., Langenfelds, R., Gomez, A., Labuschagne, C., Ramonet, M., Nakazawa, T., Metzl, N., Gillett, N., and Heimann, M.: Saturation of the Southern Ocean $CO_2$ sink due to recent climate change, Science, 316, 1735–1738, doi:10.1126/science.1136188, 2007.

Le Quéré, C., Raupach, M. R., Canadell, J. G., Marland, G., Bopp, L., Ciais, P., Conway, T. J., Doney, S. C., Feely, R. A., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R. A., House, J. I., Huntingford, C., Levy, P. E., Lomas, M. R., Majkut, J., Metzl, N., Ometto, J. P., Peters, G. P., Prentice, I. C., Randerson, J. T., Running, S. W., Sarmiento, J. L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., van der Werf, G. R., and Woodward, F. I.: Trends in the sources and sinks of carbon dioxide, Nat. Geosci., 2, 831–836, 2009.

Levy, P. E., Cannell, M. G. R., and Friend, A. D.: Modelling the impact of future changes in climate, $CO_2$ concentration and land use on natural ecosystems and the terrestrial carbon sink, Global Environ. Chang., 14, 21–30, doi:10.1016/j.gloenvcha.2003.10.005, 2004.

Marland, G.: Uncertainties in accounting for $CO_2$ from fossil fuels, J. Ind. Ecol., 12, 136–139, doi:10.1111/j.1530-9290.2008.00014.x, 2008.

Manning, A. C. and Keeling, R. F.: Global oceanic and land biotic carbon sinks from the Scripps atmospheric oxygen flask sampling network, Tellus B, 58, 95–116, doi:10.1111/j.1600-0889.2006.00175.x, 2006.

Marland, G., Andres, R. J., Blasing, T. J., Boden, T. A., Broniak, C. T., Gregg, J. S., Losey, L. M., and Treanton, K.: Energy, industry and waste management activities: An introduction to $CO_2$ emissions from fossil fuels, in: A report by the US Climate Change Science Program and the Subcommittee on Global Change Research, in The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle, edited by: King, A. W., Dilling, L., Zimmerman, G. P., Fairman, D. M., Houghton, R. A., Marland, G., Rose, A. Z., and Wilbanks, T. J., Asheville, NC, 57–64, 2007.

Marland, G., Hamal, K., and Jonas, M.: How Uncertain Are Estimates of $CO_2$ Emissions?, J. Ind. Ecol., 13, 4–7, doi:10.1111/j.1530-9290.2009.00108.x, 2009.

Masarie, K. A. and Tans, P. P.: Extension and integratino of atmospheric carbon dioxide data into a globally consistent measurement record, J. Geophys. Res.-Atmos., 100, 11593–11610, doi:10.1029/95jd00859, 1995.

McNeil, B. I., Matear, R. J., Key, R. M., Bullister, J. L., and Sarmiento, J. L.: Anthropogenic $CO_2$ uptake by the ocean based on the global chlorofluorocarbon data set, Science, 299, 235–239, doi:10.1126/science.1077429, 2003.

Meiyappan, P. and Jain, A. K.: Three distinct global estimates of historical land-cover change and land-use conversions for over 200 years, Front. Earth Sci., 6, 122–139, 2012.

Mikaloff Fletcher, S. E., Gruber, N., Jacobson, A. R., Doney, S. C., Dutkiewicz, S., Gerber, M., Follows, M., Joos, F., Lindsay, K., Menemenlis, D., Mouchet, A., Müller, S. A., and Sarmiento, J. L.: Inverse estimates of anthropogenic $CO_2$ uptake, transport, and storage by the oceans, Global Biogeochem. Cy., 20, GB2002, doi:10.1029/2005GB002530, 2006.

National Accounts Main Aggregates Database: http://unstats.un.org/unsd/snaama/Introduction.asp, last access: November 2012.

NOAA/ESRL calculation of global means: http://www.esrl.noaa.gov/gmd/ccgg/about/global_means.html, last access: November 2012.

Peters, G. P., Andrew, R., and Lennos, J.: Constructing a multi-regional input-output table using the GTAP database, Economic Systems Research, 23, 131–152, 2011a.

Peters, G. P., Minx, J. C., Weber, C. L., and Edenhofer, O.: Growth in emission transfers via international trade from 1990 to 2008, P. Natl. Acad. Sci. USA, 108, 8903–8908, doi:10.1073/pnas.1006388108, 2011b.

Peters, G. P., Andrew, R. M., Boden, T., Canadell, J. G., Ciais, P., Le Quéré, C., Marland, G., Raupach, M. R., and Wilson, C.: The challenge to keep global warming below 2 °C, Nature Climate Change, doi:10.1038/nclimate1783, in press, 2012a.

Peters, G. P., Marland, G., Le Quéré, C., Boden, T. A., Canadell, J. G., and Raupach, M. R.: Correspondence: Rapid growth in $CO_2$ emissions after the 2008–2009 global financial crisis, Nature Climate Change, 2, 2–4, 2012b.

Peylin, P., Bousquet, P., Le Quéré, C., Sitch, S., Friedlingstein, P., McKinley, G., Gruber, N., Rayner, P., and Ciais, P.: Multiple constraints on regional $CO_2$ flux variations over land and oceans, Global Biogeochem. Cy., 19, GB1011, doi:10.1029/2003GB002214, 2005.

Poulter, B., AragÃo, L., Heyder, U., Gumpenberger, M., Heinke, J., Langerwisch, F., Rammig, A., Thonicke, K., and Cramer, W.: Net biome production of the Amazon Basin in the 21st century, Glob. Change Biol., 16, 2062–2075, 2010.

Prater, M. J., Holmes, C. D., and Hsu, J.: Reactive greenhouse gas scenarios: Systematic exploration of uncertainties and the role of atmospheric chemistry, Geophys. Res. Lett., 39, L09803, doi:10.1029/2012GL051440, 2012.

Prentice, I. C., Farquhar, G. D., Fasham, M. J. R., Goulden, M. L., Heimann, M., Jaramillo, V. J., Kheshgi, H. S., Le Quéré, C., Scholes, R. J., and Wallace, D. W. R.: The Carbon Cycle and Atmospheric Carbon Dioxide, in: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 183–237, 2001.

Quay, P. D., Tilbrook, B., and Wong, C. S.: Oceanic Uptake of Fossil Fuel $CO_2$: Carbon-13 Evidence, Science, 256, 74–79, 1992.

Raupach, M. R., Marland, G., Ciais, P., Le Quéré, C., Canadell, J. G., Klepper, G., and Field, C. B.: Global and regional drivers of accelerating $CO_2$ emissions, P. Natl. Acad. Sci. USA, 104, 10288–10293, doi:10.1073/pnas.0700609104, 2007.

Schimel, D., Alves, D., Enting, I., Heimann, M., Joos, F., Raynaud, D., Wigley, T., Prater, M., Derwent, R., Ehhalt, D., Fraser, P., Sanhueza, E., Zhou, X., Jonas, P., Charlson, R., Rodhe, H., Sadasivan, S., Shine, K. P., Fouquart, Y., Ramaswamy, V., Solomon, S., Srinivasan, J., Albritton, D., Derwent, R., Isaksen, I., Lal, M., and Wuebbles, D.: Radiative Forcing of Climate Change, in: Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1995.

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K., and Venevsky, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, Glob. Change Biol., 9, 161–185, doi:10.1046/j.1365-2486.2003.00569.x, 2003.

Sitch, S., Friedlingstein, P., Gruber, N., Jones, S., Murray-Tortarolo, G., Ahlström, A., Doney, S. C., Graven, H., Heinze, C., Huntingford, C., Levis, S., Levy, P. E., Lomas, M., Poulter, B., Viovy, N., Zaehle, S., Zeng, N., Arneth, A., Bonan, G., Bopp, L., Canadell, J. G., Chevallier, F., Ciais, P., Ellis, R., Gloor, M., Peylin, P., Piao, S., Le Quéré, C., Smith, B., Zhu, Z., and Myneni, R.: Trends and drivers of regional sources and sinks of carbon dioxide over the past two decades, Biogeosciences Discuss., in review, 2012.

Smith, B., Prentice, I. C., and Sykes, M. T.: Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space, Global Ecol. Biogeogr., 10, 621–637, doi:10.1046/j.1466-822X.2001.t01-1-00256.x, 2001.

Stocker, B. D., Strassmann, K., and Joos, F.: Sensitivity of Holocene atmospheric $CO_2$ and the modern carbon budget to early human land use: analyses with a process-based model, Biogeosciences, 8, 69–88, doi:10.5194/bg-8-69-2011, 2011a.

Stocker, B. D., Strassmann, K., and Joos, F.: Sensitivity of Holocene atmospheric $CO_2$ and the modern carbon budget to early human land use: analyses with a process-based model, Biogeosciences, 8, 69–88, doi:10.5194/bg-8-69-2011, 2011b.

Strassmann, K. M., Joos, F., and Fischer, G.: Simulating effects of land use changes on carbon fluxes: past contributions to atmospheric $CO_2$ increases and future commitments due to losses of terrestrial sink capacity, Tellus, 60B, 583–603, 2008.

Tans, P. P., Fung, I. Y., and Takahashi, T.: Observational contraints on the global atmospheric $CO_2$ budget, Science, 247, 1431–1439, 1990.

Thomas, H., Prowe, A. E. F., Lima, I. D., Doney, S. C., Wanninkhof, R., Greatbatch, R. J., Schuster, U., and Corbiere, A.: Changes in the North Atlantic Oscillation influence $CO_2$ uptake in the North Atlantic over the past 2 decades, Global Biogeochem. Cy., 22, Gb4027, doi:10.1029/2007gb003167, 2008.

Tian, H., Melillo, J. M., Kicklighter, D. W., McGuire, A. D., Helfrich, J. V. K., Moore III, B., and Vorosmarty, C. J.: Effect of interannual climate variability on carbon storage in Amazonian ecosystems, Nature, 396, 644–667, 1998.

Tjiputra, J. F., Roelandt, C., Bentsen, M., Lawrence, D. M., Lorentzen, T., Schwinger, J., Seland, Ø., and Heinze, C.: Evaluation of the carbon cycle components in the Norwegian Earth System Model (NorESM), Geosci. Model Dev. Discuss., 5, 3035–3087, doi:10.5194/gmdd-5-3035-2012, 2012.

Trends in atmospheric carbon dioxide: http://www.esrl.noaa.gov/gmd/ccgg/trends, last access: July 2012.

US Geological Survey: Minerals Commodities Summaries, in: US Geological Survey, 198 pp., 2012.

United Nations Statistics Division – Energy Statistics: http://unstats.un.org/unsd/energy/, last access: October 2012a.

United Nations Statistics Division – Industry Statistics: http://unstats.un.org/unsd/industry/default.asp, last access: October 2012b.

van der Werf, G. R., Dempewolf, J., Trigg, S. N., Randerson, J. T., Kasibhatla, P., Giglio, L., Murdiyarso, D., Peters, W., Morton, D. C., Collatz, G. J., Dolman, A. J., and DeFries, R. S.: Climate regulation of fire emissions and deforestation in equatorial Asia, P. Natl. Acad. Sci. USA, 15, 20350–20355, 2008.

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), Atmos. Chem. Phys., 10, 11707–11735, doi:10.5194/acp-10-11707-2010, 2010.

Van Oss, H. G.: 2009 Minerals Yearbook, in: US Geological Survey, July 2011, 16.01–16.36, 2011.

Watson, R. T., Rodhe, H., Oeschger, H., and Siegenthaler, U.: Greenhouse Gases and Aerosols, in: Climate Change: The IPCC Scientific Assessment, Intergovernmental Panel on Climate Change (IPCC), edited by: Houghton, J. T., Jenkins, G. J., and Ephraums, J. J., Cambridge University Press, Cambridge, 1–40, 1990.

Woodward, F. I. and Lomas, M. R.: Vegetation dynamics – simulating responses to climatic change, Biological Rev., 79, 643–670, doi:10.1017/s1464793103006419, 2004.

Zaehle, S., Ciais, P., Friend, A. D., and Prieur, V.: Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions, Nat. Geosci., 4, 601–605, doi:10.1038/ngeo1207, 2011.

Zeng, N., Mariotti, A., and Wetzel, P.: Terrestrial mechanisms of interannual $CO_2$ variability, Global Biogeochem. Cy., 19, GB1016, doi:10.1029/2004gb002273, 2005.

**Table 1.** Data sources used to compute each component of the global $CO_2$ budget.

| Component | Process | Data source | Data reference |
|---|---|---|---|
| $E_{FF}$ | Fossil fuel combustion and gas flaring | UN Statistics Division to 2009<br>BP for 2010–2011 | UN (2012a, b)<br>BP (2012) |
| | Cement production | US Geological Survey | Van Oss (2011)<br>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)<br>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.<br>1980–2011: US National Oceanic and Atmospheric Administration Earth System Research Laboratory | Keeling et al. (1976)<br>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:<br>Increasing atmospheric $CO_2$ concentration<br>Climate change and variability<br>Other environmental changes | Budget residual | |

**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 |
|---|---|---|---|---|---|
| Deforestion, 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 | yes | no | no |
| Cropland harvest | yes | no | no | no | yes |
| Peat fires | from 1998 | no | no | no | no |
| Fire suppression | for US only | no | no | no | no |
| Management-Climate interactions | from 1998 | 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 |

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

| Model name | Reference |
|---|---|
| Dynamic Global Vegetation Models providing $E_{\mathrm{LUC}}$ | |
| VISIT | Kato et al. (2012)<br>Climate forcing is changed to use CRU TS3.10.01 up to the year 2009. |
| ISAM-HYDE | Jain et al. (2012) |
| LPJmL | Poulter et al. (2010) |
| LPJ-Bern | Stocker et al. (2011a); Strassmann et al. (2008) |
| Dynamic Global Vegetation Models providing $S_{\mathrm{LAND}}$ | |
| 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 $S_{\mathrm{OCEAN}}$ | |
| 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. (2012) |

**Table 4.** Decadal mean in the five components of the anthropogenic $CO_2$ budget for the periods 1980–1989, 1990–1999, 2000–2009 and the last decade available. All values are in PgC yr$^{-1}$.

| | mean (PgC yr$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | 1960–1969 | 1970–1989 | 1980–1989 | 1990–1999 | 2000–2009 | 2002–2011 |
| Emissions | | | | | | |
| Fossil fuel combustion and cement production ($E_{\mathrm{FF}}$) | 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 ($E_{\mathrm{LUC}}$) | 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 ($G_{\mathrm{ATM}}$) | 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 ($S_{\mathrm{OCEAN}}$) | 1.5 ± 0.5 | 1.7 ± 0.5 | 2.0 ± 0.5 | 2.2 ± 0.4 | 2.3 ± 0.5 | 2.5 ± 0.5 |
| Residual terrestrial sink ($S_{\mathrm{LAND}}$) | 1.3 ± 0.7 | 1.5 ± 0.8 | 1.5 ± 0.8 | 2.6 ± 0.8 | 2.5 ± 0.8 | 2.6 ± 0.8 |

**Table 5.** Actual $CO_2$ emissions from fossil fuel combustion and cement production ($E_{\mathrm{FF}}$) compared to projections made the previous year based on world GDP and the fossil fuel intensity of GDP ($I_{\mathrm{FF}}$). 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 |
| $E_{\mathrm{FF}}$ | –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 % |
| $I_{\mathrm{FF}}$ | –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. (2012b).

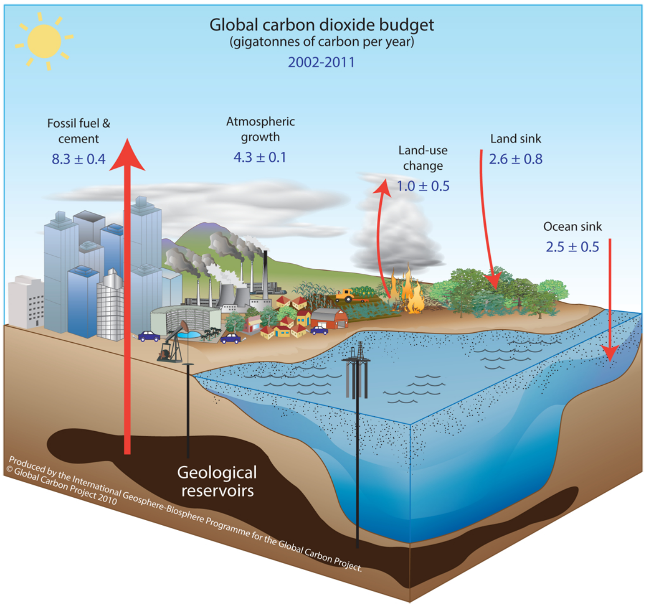

**Fig. 1.** Schematic representation of the overall perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2002–2011. The arrows represent emission from fossil fuel burning and cement production; emissions from deforestation and other land-use change; 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 $\mathrm{PgC\,yr^{-1}}$, 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).

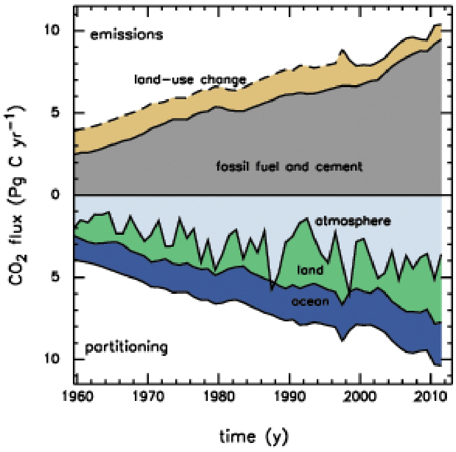

**Fig. 2.** Combined components of the global carbon budget illustrated in Fig. 1 as a function of time, for (top) emissions from fossil fuel combustion and cement production ($E_{\mathrm{FF}}$; grey) and emissions from land-use change ($E_{\mathrm{LUC}}$; brown), and (bottom) their partitioning among the atmosphere ($G_{\mathrm{ATM}}$; light blue), land ($S_{\mathrm{LAND}}$; green) and oceans ($S_{\mathrm{OCEAN}}$; 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.

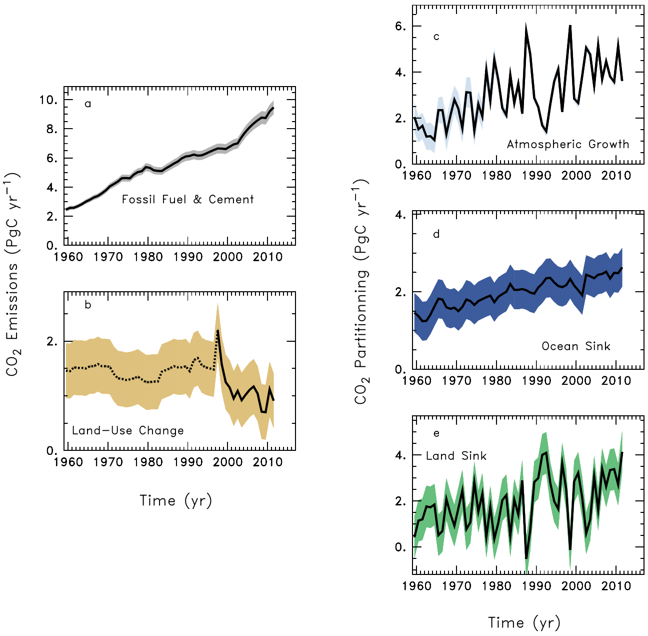

**Fig. 3.** Components of the global carbon budget and their uncertainties as a function of time, presented individually for **(a)** emissions from fossil fuel combustion and cement production ($E_{\mathrm{FF}}$), **(b)** emissions from land-use change ($E_{\mathrm{LUC}}$) with management-climate interactions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

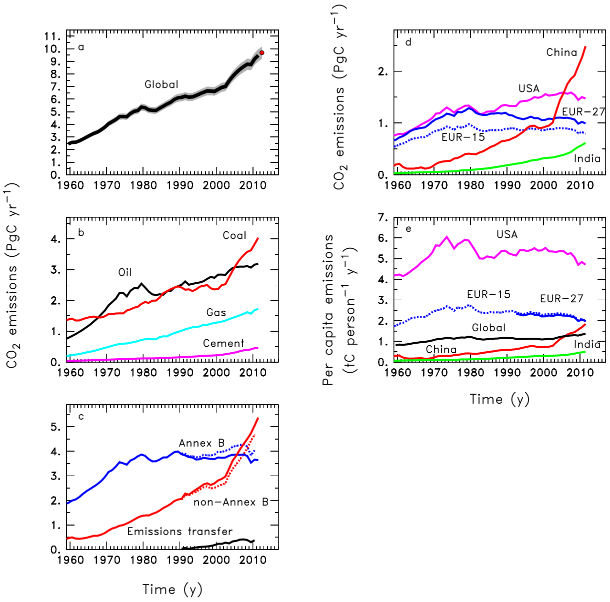

**Fig. 4.** CO$_2$ emissions from fossil fuel combustion and cement production for **(a)** the globe, including an uncertainty of ±5 % (grey shading) and the emissions projection for year 2012 based on GDP projection (red dot), **(b)** global emissions by fuel type, including coal (red), oil (black), 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**). 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.

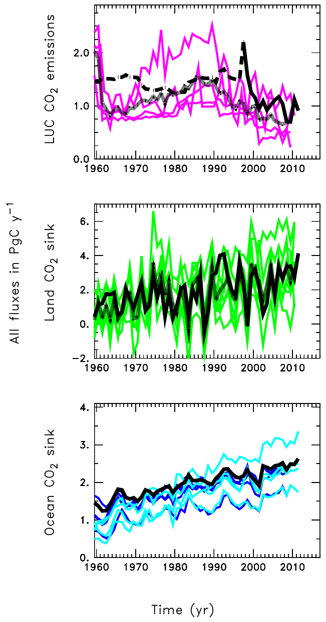

**Fig. 5.** Comparison of (top panel) CO$_2$ emissions from land-use change (LUC), (middle panel) land CO$_2$ sink ($S_{\text{LAND}}$), and (bottom panel) ocean CO$_2$ sink ($S_{\text{OCEAN}}$) between the CO$_2$ budget values estimated here (black line), and those estimated from process models (Table 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. For the ocean CO$_2$ sink, the four models used in Le Quéré et al. (2009) are shown in dark blue, while the updated and models used to calculate interannual variability after 2008 are shown in pale blue.

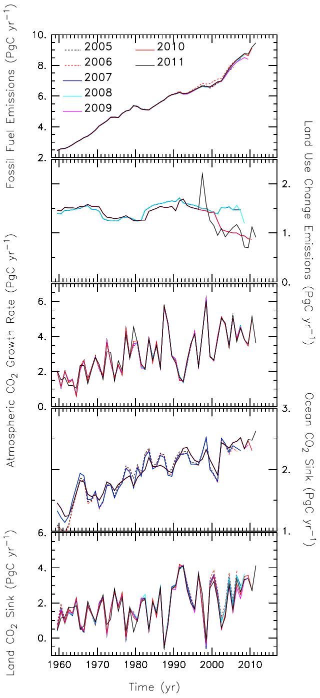

**Fig. 6.** Comparison of global carbon budget components released annually by GCP since 2005. $CO_2$ emissions from both **(a)** fossil fuel combustion and cement production, and **(b)** land-use change, and their partitioning among **(c)** the atmosphere, **(d)** the ocean, and **(e)** the land. The 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. (2012b), and (black) this study. All values are in $PgC\,yr^{-1}$.