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Trends in the sources and sinks of carbon dioxide

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Efforts to control climate change require the stabilization of atmospheric CO_2 concentrations. This can only be achieved through a drastic reduction of global CO_2 emissions. Yet fossil fuel emissions increased by 29% between 2000 and 2008, in conjunction with increased contributions from emerging economies, from the production and international trade of goods and services, and from the use of coal as a fuel source. In contrast, emissions from land-use changes were nearly constant. Between 1959 and 2008, 43% of each year's CO_2 emissions remained in the atmosphere on average; the rest was absorbed by carbon sinks on land and in the oceans. In the past 50 years, the fraction of CO_2 emissions that remains in the atmosphere each year has likely increased, from about 40% to 45%, and models suggest that this trend was caused by a decrease in the uptake of CO_2 by the carbon sinks in response to climate change and variability. Changes in the CO_2 sinks are highly uncertain, but they could have a significant influence on future atmospheric CO_2 levels. It is therefore crucial to reduce the uncertainties.

Atmospheric measurements of CO_2 concentration are highly precise and provide an accurate, reliable measure of the increase of CO_2 in the atmosphere every year[1]. Yet these measurements cannot at present be used to verify global CO_2 emissions estimated from energy data, because the uptake of CO_2 by the land and ocean CO_2 sinks are not quantified with high enough accuracy. Understanding the difference in amount between anthropogenic CO_2 emissions and changes in atmospheric CO_2 concentration requires good estimates of the sinks and good attribution of the causes of changes, both for the emissions and for their partitioning between the natural reservoirs.

Global CO_2 emissions and their partitioning between the atmosphere and the land and ocean CO_2 sinks can be established using a wide range of geophysical and economic data. We have constructed a global CO_2 budget for each year during 1959–2008 and analysed the underlying drivers of each component. The global increase in atmospheric CO_2 was determined directly from measurements. CO_2 emissions from fossil fuel combustion were estimated on the basis of countries' energy statistics. CO_2 emissions from land-use change (LUC) were estimated using deforestation and other land-use data, fire observations from space, and assumptions on the carbon density of vegetation and soils and the fate of carbon. The time evolution of the land and ocean CO_2 sinks, however, cannot be estimated directly from observations. For these terms, we used state-of-the-art models on which we imposed the observed meteorological conditions of the past few decades. The resulting global CO_2 budget provides insight into the global carbon cycle and the emerging trends.

Fossil fuel CO_2 emissions

CO_2 emissions from fossil fuel combustion, including small contributions from cement production and gas flaring, were 8.7±0.5 Pg C yr^{-1} in 2008, an increase of 2.0% on 2007, 29% on 2000 and 41% above emissions in 1990 (Supplementary Table 1; see Methods). Emissions increased at a rate of 3.4% yr^{-1} between 2000 and 2008, compared with 1.0% yr^{-1} in the 1990s (Fig. 1). Emissions continued to track the average of the most carbon-intensive family of scenarios put forward by the Intergovernmental Panel on Climate Change[2,3] (IPCC; scenario A1FI in Fig. 1a). Since 1990, the growth in fossil fuel CO_2 emissions has been dominated by countries that do not have emissions limitations in the so-called non-Annex B of the Kyoto Protocol (mostly emerging economies in developing countries), where emissions have more than doubled in that time (Fig. 1b). Among Annex B countries (mostly advanced economies with emissions limitations), growth in some has been offset by declines in others. This recent growth in CO_2 emissions parallels a shift in the largest fuel emission source from oil to coal. Coal contributed 40% of the fossil fuel CO_2 emissions in 2008, compared with 37% for 1990–2000, whereas the contribution of oil changed from 41% for 1990–2000 to 36% in 2008 (Fig. 1c). This shift in the dominant source of fossil fuel emissions has reversed the prevalence of oil since 1968. The growth in emissions since 2000 was also accompanied by an increase in the world per-capita emissions from 1.1 metric tons of carbon in 2000 (Fig. 1d) to an all-time high of 1.3 metric tons of carbon in 2008.

There is growing evidence that the rapid growth in international trade[4–10] and a shift of Annex B economic activity towards services[8] were significant in driving non-Annex B CO_2 emission increases due to fossil fuels. Several recent studies provide indicators of the magnitude and time evolution of the share of non-Annex B emission growth that was due to production of manufactured products exported and consumed in Annex B countries. In 2001, the equivalent of 0.22 Pg C was emitted in non-Annex B countries to produce internationally traded products consumed in Annex B countries[4]. In China alone, 30% of the growth in emissions between 1990 and 2002 was attributable to the production of exports from China that were consumed in other countries[6], and the share of the growth increased to 50% between 2002 and 2005 (ref. 7). In 1990, 16% of Chinese emissions were from the production of exports, increasing to 30% in 2005. Over half of the exported products were destined for Annex B countries[6,7]. Complementary studies in some Annex B countries showed that consumption-based emissions (that is, emissions including imported products from non-Annex B countries, but excluding goods and services) were increasing faster than emissions from domestic production[8,9]. In the UK, for instance, within-country emissions decreased by 5% between 1992 and 2004, whereas consumption-based emissions increased by 12% (ref. 8). In the USA, within-country emissions increased by 6% between 1997 and 2004, whereas consumption-based emissions increased by 17% (ref. 9). In both cases, a key factor driving the growth in consumption-based emissions was the import of manufactured products from China[6–9]. Taken together, these studies imply that a considerable share of the growth of emissions from non-Annex B countries was associated with international trade. This explained around one-quarter of the growth in non-Annex B emissions since 2000.

The growth in the world gross domestic product (GDP) was a key driver in the recent increase in CO_2 emissions[2]. Consequently,

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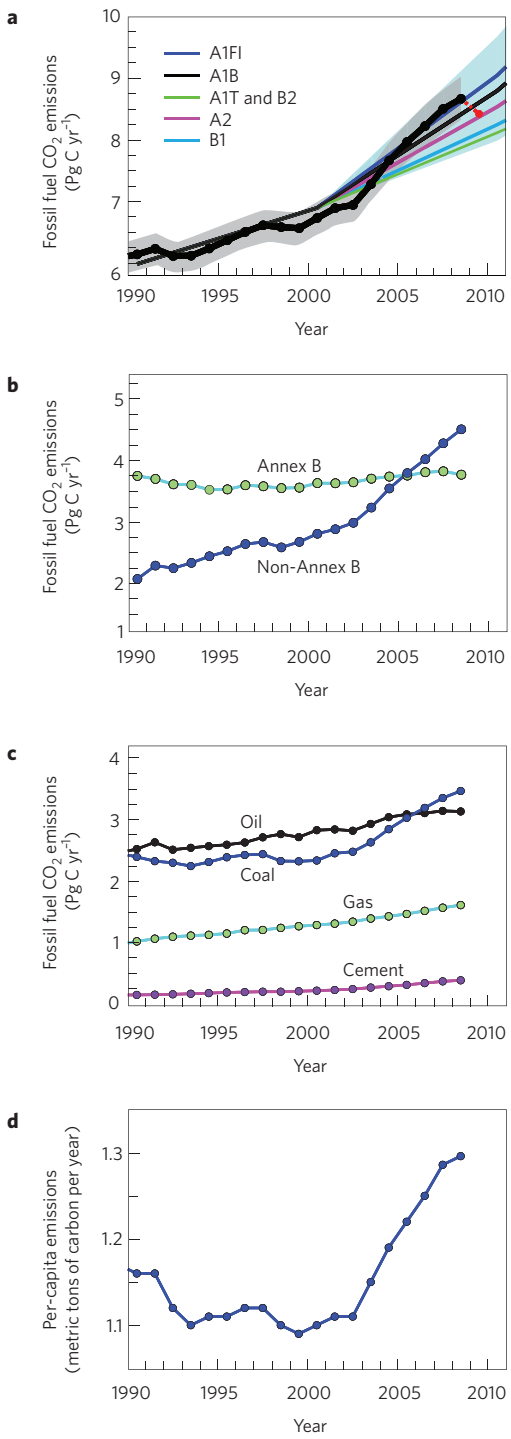

Figure 1 | Fossil fuel CO_2 and per-capita emissions since 1990. **a**–**c**, Fossil fuel emissions for the globe (**a**), Annex B countries (mostly advanced economies; green) and non-Annex B countries (mostly developing countries; blue) (**b**) and, specifically, coal (blue), oil (black), gas combustion (green) and cement production (purple) (**c**). The data in all panels are the annual mean data. Panel **a** also shows the projections averaged by scenario family from the IPCC Special Report on Emissions Scenarios (full coloured lines[3]), as in ref. 2. The grey shading in **a** is the uncertainty in emissions. The blue shading covers all CO_2 emissions scenarios used to project climate by the IPCC Fourth Assessment Report. The red dot and dashed line in **a** are the projected CO_2 emissions for 2009 (see text). **d**, Global per-capita emissions.

the global financial crisis that affected markets in 2008 also had an effect on the global CO_2 emissions and probably explains the modest growth in emissions of 2.0% since 2007, compared with the faster than average growth of 3.6% yr^{-1} observed for 2000–2007. We predict a decrease of 2.8% in global CO_2 emissions for 2009 using the change in GDP projected by the International Monetary Fund (−1.1% as of October 2009) and assuming that the carbon intensity of world GDP has continued to improve following its long-term trend of −1.7% yr^{-1} (refs 11, 12; Fig. 1a). The abrupt decrease in GDP in 2009 could bring global CO_2 emissions back to just below their 2007 level and into the middle range of the emissions scenarios that were used by the IPCC to project climate this century[3]. The evolution of global CO_2 emissions after 2009 will depend on the subsequent trends in GDP and on the evolution of the carbon intensity of GDP, for instance as a result of countries following international agreements to curb CO_2 emissions.

Land-use change CO_2 emissions

Emissions from LUC are the second-largest anthropogenic source of CO_2. Deforestation, logging and intensive cultivation of cropland soils emit CO_2. These emissions are partly compensated by CO_2 uptake from the regrowth of secondary vegetation and the rebuilding of soil carbon pools following afforestation, abandonment of agriculture (including the fallow phase of shifting cultivation), fire exclusion and the shift to agricultural practices that conserve soil carbon. Unlike fossil fuel emissions, which reflect instantaneous economic activity, LUC emissions are due to both current deforestation and the carry-over effects of CO_2 losses from areas deforested in previous years.

Here we have used a revised estimate[11] of the net CO_2 flux resulting from LUC based on United Nations data for LUC areas (available until 2005) and a book-keeping method[13]. For the period 1990–2005, net LUC CO_2 emissions were 1.5±0.7 Pg C yr^{-1}, and were dominated by tropical deforestation. In the deforestation process, fire is the primary means by which forests are converted to pastures or croplands[14], after timber exploitation. To estimate LUC emissions after 2005, we used emissions due to fire in deforestation areas[15] as a proxy for deforestation emissions (Methods).

In 2008, the fire emissions associated with deforestation were 0.3 Pg C yr^{-1} less than their 1997–2008 average of 0.7 Pg C yr^{-1}, with the largest reductions being in southeast Asia (−65%) and tropical America (−40%). Lower-than-average deforestation rates reported in the Brazilian Amazon rainforest[16] corroborate lower LUC emissions in 2008 in tropical America. Combining the long-term average global LUC flux, 1.5 Pg C yr^{-1}, with the 2008 deforestation fire anomaly, −0.3 Pg C yr^{-1}, our best estimate for 2008 LUC emissions is 1.2 Pg C yr^{-1}. Wet La Niña conditions in 2008 probably limited fire use and deforestation rates in southeast Asia, particularly in Indonesia[17]. In the Amazon basin, climate conditions were not anomalous, suggesting that other factors caused the decrease in 2008 deforestation rates, which for the Brazilian Amazon rainforest was the continuation of a decreasing trend following high deforestation rates in 2002–2004 (ref. 16).

Taken together, the total CO_2 emission from fossil fuel combustion and LUC was 9.9±0.9 Pg C yr^{-1} in 2008. The relative contribution of LUC CO_2 emissions to total anthropogenic CO_2 emissions decreased from 20% in 1990–2000 to 12% in 2008, owing to increasing fossil fuel emissions and below-average deforestation emissions in 2008. Although LUC emissions were the smaller factor, their uncertainty, ±0.7 Pg C yr^{-1}, is larger than the uncertainty of ±0.5 Pg C yr^{-1} associated with fossil fuel emissions (Methods).

Atmospheric CO_2 growth and CO_2 sinks

On average, 43% of the total CO_2 emissions each year between 1959 and 2008 remained in the atmosphere, but this fraction is

subject to very large year-to-year variability (Fig. 2a). This 'airborne fraction' increased on average by 0.3±0.2% yr^{-1} between 1959 and 2008. There is a 90% probability that this increasing trend is significant taking into account the background variability (Methods). The trend and its significance are sensitive to estimates of LUC emissions, which have large uncertainties. We quantified the impact of LUC uncertainty on the airborne-fraction trend using a range of LUC estimates (Supplementary Information). For all nine published LUC estimates considered, the trend in the airborne fraction was positive with a significance level at or above 90%. We conclude that a positive trend in the airborne fraction is 'likely' (66% confidence interval), according to the terminology developed by the IPCC[18].

A positive trend in the airborne fraction could be explained by several factors. First, the atmospheric CO_2 concentration could be increasing on a timescale shorter than those regulating the rate of uptake of carbon sinks. Second, both the land and ocean CO_2 sinks are expected to decrease in efficiency at high ambient CO_2 concentration because of the limits of CO_2 fertilization on land and the decrease in carbonate concentration, which buffers CO_2 in the ocean[19]. Third, the land and/or ocean CO_2 sink could be responding to climate variability and change. Finally, sink processes not considered in current models may be contributing to the observed changes[19].

Combined evidence from atmosphere and ocean observations constrains the mean uptake rates of land and ocean CO_2 sinks to 2.6±0.7 and 2.2±0.4 Pg C yr^{-1} for 1990–2000, respectively[11,19–22]. We estimated the year-to-year variability and trends in the land and ocean CO_2 sinks using a series of global models that represent the complex processes governing the carbon cycle in these two pools (Methods). The models were forced by observed changes in global atmospheric CO_2 concentration and by variable climate fields.

For 2008, the models estimated that the uptake rates for land and ocean CO_2 sinks were 4.7±1.2 and 2.3±0.4 Pg C yr^{-1}, respectively. The land CO_2 sink was larger (in terms of uptake rate) and the ocean CO_2 sink was smaller in 2008, relative to the previous three years (Fig. 2), because the El Niño/Southern Oscillation (ENSO) was in a positive (La Niña) state in 2008. During La Niña conditions, the land CO_2 sink is enhanced owing to lower temperatures and wetter conditions in the tropics, whereas the ocean CO_2 sink is reduced owing to more intense equatorial upwelling of carbon-rich waters. Observations in the equatorial Pacific Ocean corroborate the lower ocean CO_2 sink in 2008 (ref. 23) estimated by the models. The ocean models also attributed the low ocean CO_2 sink in 2008 in part to a weaker Southern Ocean sink, in response to the continuing increase in the southern annular mode[24,25]. The model results over 1980–2006 were broadly consistent with the results from atmospheric inverse models, which estimate the regional distribution of air–surface CO_2 fluxes using the spatiotemporal variability in atmospheric CO_2 concentration measurements[26,27] (Supplementary Information).

The land biosphere models showed an increasing global land CO_2 sink between 1959 and 2008 (Fig. 2c), with large year-to-year variability. The variability was primarily driven by variability in precipitation, surface temperature and radiation[28–30]. During 1959–2008, the fraction of the total CO_2 emissions that was absorbed by the land had no significant global trend. The ocean models showed an increasing global ocean CO_2 sink between 1959 and 2008 (Fig. 2d), with small year-to-year variability compared with the land sink. The modelled CO_2 sink increased at a lower rate than the emissions, and the fraction of the total CO_2 emissions that was absorbed by the oceans decreased by 0.60±0.15% yr^{-1} (Supplementary Table 1) as a result. The long-term decrease in the fraction of the emissions taken up by the oceans cannot be verified from ocean observations alone because of the lack of global data coverage[31]. However,

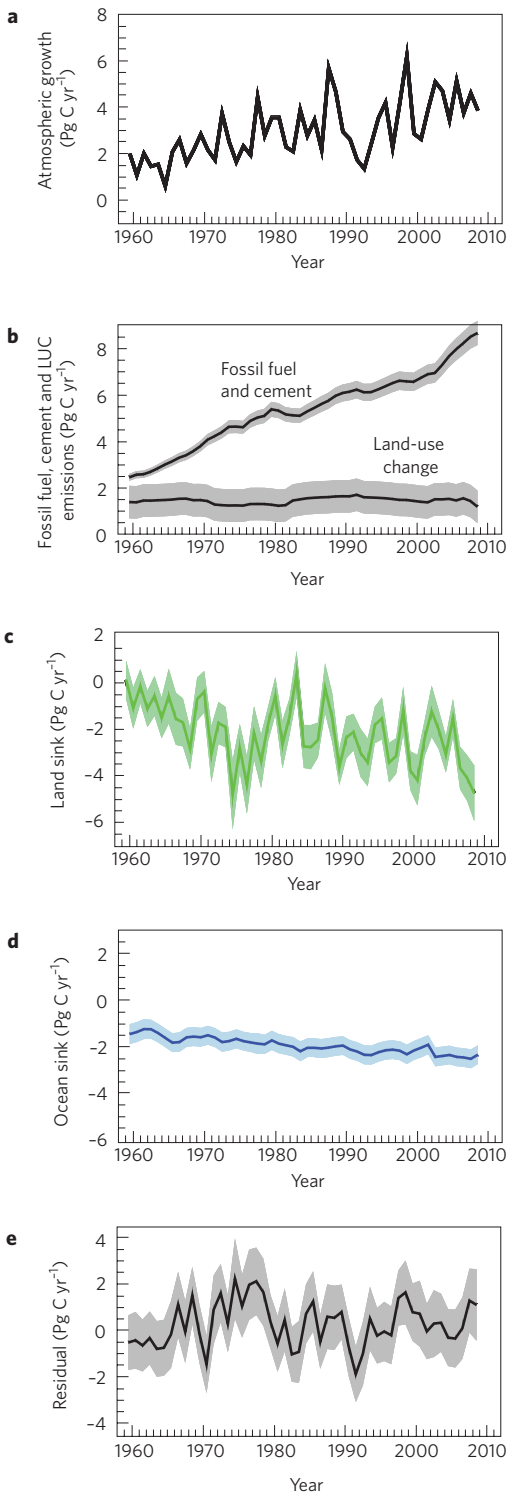

Figure 2 | Components of the global CO_2 budget. a, The atmospheric CO_2 growth rate. **b**, CO_2 emissions from fossil fuel combustion and cement production, and from LUC. **c**, Land CO_2 sink (negative values correspond to land uptake). **d**, Ocean CO_2 sink (negative values correspond to ocean uptake). **e**, The residual sum of all sources and sinks. The land and ocean sinks (**c**,**d**) are shown as an average of several models normalized to the observed mean land and ocean sinks for 1990–2000 (refs 11,19). The shaded area is the uncertainty associated with each component. See Methods for the sources of data and an explanation of uncertainties.

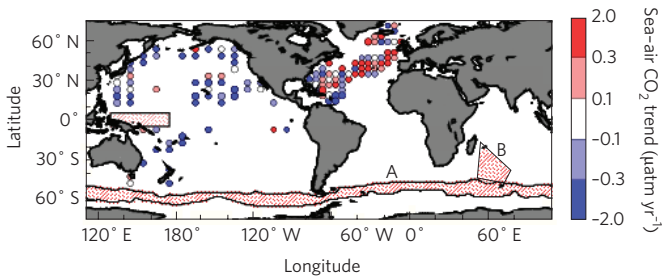

Figure 3 | Trends in the observed partial pressure of CO_2 for ocean minus air, for 1981–2007. The observed trends are calculated by fitting a linear trend to repeated measurements of surface-ocean and air CO_2 as in refs 31 and 32. Positive (red) values indicate regions where the partial pressure of CO_2 in the ocean is increasing faster than atmospheric CO_2. Large, medium and small dots are plotted for trends with errors of <0.25, 0.25–0.50 and >0.50 µatm yr^{-1}, respectively. In southern circumpolar waters (A), the trends were estimated from austral winter data[31]. In the South Indian Ocean (B), the trends were estimated for 1991–2007 (ref. 34) only.

a weakening of the regional CO_2 sinks has been observed since at least 1990 (Fig. 3), from repeated surface-ocean CO_2 observations in the North Atlantic Ocean[32,33] and in the Southern Ocean[31,34], and from the spatial distribution of atmospheric CO_2 increases in the Southern Ocean[24]. These observations suggest that in some ocean regions, the ocean carbon cycle is responding to climate variability and climate change in a way that can affect the net uptake of CO_2 by the ocean. In contrast, increasing air–sea CO_2 flux was observed in the North Pacific Ocean[35].

We identified the drivers of the trends in land and ocean CO_2 sinks in the models by forcing a subset of the models with increasing atmospheric CO_2 concentration alone (no changes in climate; see Supplementary Information). These additional simulations isolate the effect of climate from the combined effects of rapidly rising CO_2 and high ambient CO_2 concentration. In all models tested, the land and ocean CO_2 sinks increased at the same rate (in one model) or faster (in six models) when climate did not change. We combined the land and ocean CO_2 sinks estimated by the models with the emissions to reproduce the time evolution of the airborne fraction. The model-based airborne fraction decreased at a rate of 0.8% yr^{-1} when the models were forced by increasing CO_2 concentration alone, and increased at a rate of 0.1% yr^{-1} (close to the rate of 0.3% yr^{-1} estimated from observations) when the models were forced by both increasing CO_2 concentration and changes in climate. These simulations do not completely exclude a role for rapidly rising CO_2 or high ambient CO_2 concentration because the models are subject to uncertainty, particularly due to their coarse resolution[36] in the ocean and to errors in observed precipitation and radiation on land.

Our estimates of sources and sinks of CO_2 were based on largely independent data and methods. Thus, when all the sources and sinks were summed every year they did not necessarily add to zero, because of the errors in the various methods. The sum of all CO_2 sources and sinks, which we call the 'residual', spanned a range of ±2.1 Pg C yr^{-1} (Fig. 2e). This residual was not explained by the atmospheric CO_2 growth rate, the CO_2 emissions from fossil fuel combustion or the ocean uptake, because the uncertainties in these components were much smaller than the variability of the residual. Errors in LUC flux may explain a small part of the residual, for instance during the late 1990s, when fires in Indonesia were partly caused by land clearance taking advantage of the drought conditions[17]. Our fire-based LUC anomalies for 1997 were 0.7 Pg C greater than normal and account for one-half of the residual for that year. Overall, the residual was most probably caused by the regional responses of terrestrial vegetation to climate variability, indicating that land models overestimated the response of vegetation to the relatively cool/wet La Niña-like climatic conditions of the mid 1970s and underestimated the response to the volcanic eruption of Mount Pinatubo, in the Philippines, in the early 1990s. This later underestimation has been explained elsewhere as resulting from a missing response in the models to the aerosol-induced increase in the diffuse-light component of surface irradiance, and the subsequent enhancement of light penetration into vegetation canopies[29].

As a result of all CO_2 sources and sinks, atmospheric CO_2 growth was 3.9±0.1 Pg C yr^{-1} in 2008, an increase of 1.8 ppm, which is 0.6 Pg C yr^{-1} less than the average of the previous three years despite there being an increase in CO_2 emissions from fossil fuel combustion. Average atmospheric CO_2 in 2008 reached a concentration of 385 ppm, which is 38% above pre-industrial levels. The lower-than-average atmospheric growth rate was probably driven by a high land CO_2 uptake due to the La Niña state of ENSO, and by reduced rates of deforestation in southeast Asia and in the Amazon[16], as indicated by lower rates of fire and clear-cut activities measured at the deforestation frontier.

Filling the gaps in the global CO_2 budget

Progress has been made in monitoring the trends in the carbon cycle and understanding their drivers. However, major gaps remain, particularly in our ability to link anthropogenic CO_2 emissions to atmospheric CO_2 concentration on a year-to-year basis; this creates a multi-year delay and adds uncertainty to our capacity to quantify the effectiveness of climate mitigation policies. To fill this gap, the residual CO_2 flux from the sum of all known components of the global CO_2 budget needs to be reduced, from its current range of ±2.1 Pg C yr^{-1}, to below the uncertainty in global CO_2 emissions, ±0.9 Pg C yr^{-1}. If this can be achieved with improvements in models and observing systems, geophysical data could provide constraints on global CO_2 emissions estimates.

The likely recent trend in the airborne fraction of the total emissions suggests that the growth in uptake rate of CO_2 sinks is not keeping up with the increase in CO_2 emissions[11]. The models used here indicate that this trend could be due to the response of the land and ocean CO_2 sinks to climate variability and climate change. If the model response to recent changes in climate is correct, this would lend support to the positive feedback between climate and the carbon cycle that was predicted by many coupled climate–carbon cycle models[37]. However, these models do not yet include many processes and reservoirs that may be important, such as peat, buried carbon in permafrost soils, wild fires, ocean eddies and the response of marine ecosystems to ocean acidification. An improved knowledge of regional trends would help to constrain the climate–carbon cycle feedback better.

The current growth in global anthropogenic CO_2 emissions is tightly linked to the growth in GDP. On the basis of the projected changes in GDP, it is likely that CO_2 emissions in 2009 will revert to their 2007 levels. The key to sustained emissions reductions after the global economy recovers lies in restructuring the primary energy use to decouple emissions from GDP[12].

Methods

Original data to complete the global CO_2 budget are generated by multiple agencies and research groups around the world and are collated annually by the Global Carbon Project (http://www.globalcarbonproject.org). CO_2 emissions from fossil fuel and other industrial processes between 1959 and 2006 were based on United Nations Energy Statistics and cement data from the US Geological Survey[38], and were provided by the Carbon Dioxide Information Analysis Center. For 2007 and 2008, increases in fossil fuel emissions were calculated using BP energy data[39,40] and increases in cement emissions were based on the preliminary data[41] on 20 of the largest producers (amounting to over 80% of total global production), assuming

the same fractional change as in 2005–2006 for smaller producers. The gas-flaring emissions for 2006 were also used for 2007 and 2008. Per-capita emissions were compiled by the Carbon Dioxide Information Analysis Center between 1959 and 2006. For 2007 and 2008, per-capita emissions were based on our global CO_2 emissions and world population from the US Census Bureau. We used an uncertainty in CO_2 emissions of ±6% (ref. 42), representing a 1σ (66%) confidence interval. This uncertainty was revised upwards from the 5% used in ref. 11 beccause of the larger share of global emissions from non-Annex B countries.

We calculated CO_2 emissions from LUC using a book-keeping method[13] with the revised statistical data from the Food and Agriculture Organization of the United Nations Global Forest Resource Assessment[43], as in ref. 11. We used fire emissions estimates from the Oak Ridge National Laboratory Distributed Active Archive Center's Global Fire Emissions Database, version 2, where information on burned area and fire activity from various satellite sensors[44] is combined with a biogeochemical model to estimate carbon stocks and combustion parameters[45]. We sampled only those 1° × 1° grid cells undergoing active deforestation during the 2000–2005 period, using existing maps[46]. Emissions from the 'maintenance fires' (for example pasture burning) at the deforestation frontier are probably an order of magnitude lower than deforestation emissions because of lower fuel loads in pasture and cropland ecosystems[45]; in our analyses, we therefore included 90% of the total estimated emissions. The use of fire estimates assumes that year-to-year changes in fire CO_2 emissions were the main cause of interannual variability in LUC emissions and that the delayed emissions from decomposition were relatively constant. The variability in LUC estimated from fire emissions correlated with the variability estimated by the book-keeping method when they overlap (correlation coefficient, $r = 0.54$; $n = 12$). We used an uncertainty of ±0.7 Pg C yr^{-1}, representing a 1σ (66%) confidence interval. This uncertainty was revised upwards from the ±0.5 Pg C yr^{-1} used in ref. 11, to acknowledge recently identified inconsistencies between deforestation and agricultural conversion statistics (see Supplementary Information).

The data on annual growth in atmospheric CO_2 concentration was provided by the US National Oceanic and Atmospheric Administration Earth System Research Laboratory (http://www.esrl.noaa.gov/gmd/ccgg/trends). We used the global mean data after 1980 and the Mauna Loa data between 1959 and 1980. The land CO_2 sink was estimated using five global vegetation models updated from ref. 28 (see Supplementary Information). The models represent the processes governing ecosystem carbon dynamics in biomass, litter and soil pools and the space–time distribution of CO_2 fluxes exchanged with the overlying atmosphere. All models were forced by observed atmospheric CO_2 concentration and a combination of meteorological fields from the Climatic Research Unit observed climate data and the US National Centers for Environmental Prediction reanalysis product[47]. The ocean CO_2 sink was estimated using four ocean general circulation models coupled to ocean biogeochemistry models[24,48–50]. The models represent the physical, chemical and biological processes governing the marine carbon cycle and the space–time distribution of CO_2 fluxes exchanged with the overlying atmosphere. All models were forced by meteorological fields from the US National Centers for Environmental Prediction reanalysis product[47]. The land and ocean CO_2 sinks were estimated from the mean of all models. We corrected the model mean to agree with the observed uptake rates for land and ocean CO_2 sinks in 1990–2000 (refs 11,19). Thus, the models were used to assess the year-to-year variability and trends in the land and ocean CO_2 sinks only. The uncertainty for a given time period combined the uncertainty for 1990–2000 (ref. 19) and ±1 mean absolute deviation for all models around the central model estimate for the given period (see Supplementary Information).

The significance of the trend in airborne fraction was computed from the monthly deseasonalized atmospheric CO_2 data as detailed in ref. 11. The noise in the airborne fraction was reduced by removing the part of the variability associated with the ENSO and volcanic-activity indices. The statistical significance was computed from a 1,000-member Monte Carlo simulation with noise properties similar to those of the airborne fraction. The standard deviation of the 1,000-member simulation provided the uncertainty in the results.

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Author contributions

C.L.Q., M.R.R., J.G.C., G.M., R.A.H., P.C. and P. Friedlingstein conceived and designed the global CO_2 budget. G.M. estimated the fossil fuel emissions and G.P.P. estimated the emissions from the production and international trade of goods and services. R.A.H., G.R.v.d.W. and J.T.R. estimated LUC emissions and were helped by J.G.C., J.P.O. and J.I.H. in their interpretation. S.S., N.V., P.C., P. Foster, P. Friedlingstein, C.H., P.E.L., M.R.L., F.I.W. and I.C.P. designed and performed the land model simulations and were helped by S.W.R. in their interpretation. C.L.Q., L.B., S.C.D., J.M. and J.L.S. designed and performed the ocean model simulations. R.A.F., N.M., U.S. and T.T. provided and analysed the ocean CO_2 observations, and T.J.C. provided and analysed the atmospheric CO_2 observations. K.G. provided updated atmospheric CO_2 inversions. M.R.R. and C.L.Q. computed and analysed the trends in sources, sinks and airborne fraction. S.S., P. Friedlingstein and C.L.Q. analysed the residual with the help of all authors. All authors co-wrote the paper.

Additional information

Supplementary information accompanies this paper on www.nature.com/naturegeoscience.

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