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SUPPLEMENTARY INFORMATION

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Trends in the sources and sinks of carbon dioxide

Corinne Le Quéré[1,2], Michael R. Raupach[3], Josep G. Canadell[3], Gregg Marland[4], Laurent Bopp[5], Philippe Ciais[5], Thomas J. Conway[6], Scott C. Doney[7], Richard A. Feely[8], Pru Foster[9], Pierre Friedlingstein[5,9], Kevin Gurney[10], Richard A. Houghton[11], Johanna I. House[9], Chris Huntingford[12], Peter E. Levy[13], Mark R. Lomas[14], Joseph Majkut[15], Nicolas Metzl[16], Jean P. Ometto[17], Glen P. Peters[18], I. Colin Prentice[9], James T. Randerson[19], Steven W. Running[20], Jorge L. Sarmiento[14], Ute Schuster[1], Stephen Sitch[21], Taro Takahashi[22], Nicolas Viovy[5], Guido R. van der Werf[23], F. Ian Woodward[13]

[1]School of Environment Sciences, University of East Anglia, Norwich, NR4 7TJ, UK;

[2]British Antarctic Survey, High Cross, Madingley Road, Cambridge BC3 0ET;

[3]Global Carbon Project, CSIRO Marine and Atmospheric Research, Canberra, ACT 2601, Australia;

[4]Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6335, USA ;

[5]Laboratoire des Sciences du Climat et de l'Environnement, UMR 1572 CEA-CNRS-UVSQ, Gif sur Yvette, 91191;

[6]NOAA Earth System Research Laboratory, Boulder, Colorado 80305, USA;

[7]Woods Hole Oceanographic Institution, Clark 424, MS#25, Woods Hole, MA 02543, USA;

[8]Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115;

[9]Department of Earth Sciences, University of Bristol, Bristol, BS8 1RJ, UK;

[10]Dept of Earth and Atmospheric Sciences & Dept of Agronomy, Purdue Univ, IN 47907-2051, USA;

[11]Woods Hole Research Center, Falmouth, MA 02540, USA;

[12]Centre for Ecology and Hydrology, Wallingford, Benson Land, OX108BB, UK;

[13]Centre for Ecology and Hydrology, Bush Estate, Penicuik, Midlothian, EH26 0QB UK;

[14]Department Animal & Plant Sciences, University of Sheffield, S10 2TH, UK

[15]AOS Program, Princeton University, P.O. Box CV710, Princeton, USA;

[16]LOCEAN-IPSL, CNRS, Institut Pierre Simon Laplace, Université P. et M. Curie - Case 100, 4, place Jussieu - 75252 Paris Cedex 5, France;

[17]Instituto Nacional de Pesquisas Espaciais (INPE), Av. dos Astronautas, 1758, 12227-010, São José dos Campos, SP, Brazil ;

[18]Center for International Climate and Environmental Research – Oslo, Pb. 1129 Blindern, N-0318 Oslo, Norway;

[19]Department of Earth System Science, University of California, Irvine, CA 92697, USA;

[20]School of Forestry/Numerical Terradynamic Simulation Group, University of Montana, Missoula MT 59812, USA;

[21]School of Geography, University of Leeds, Leeds, LS2 9JT, UK;

[22]Lamont-Doherty Earth Observatory of Columbia University, 61 Route 9W - PO Box 1000, Palisades, NY 10964-8000, USA;

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[23]Faculty of Earth and Life Sciences, VU University, Amsterdam, Netherlands.

Supplementary information

1. Global CO_2 budget

The global CO_2 budget presented in this report can be found on the web site of the Global Carbon Project at: http://www.globalcarbonproject.org

Table S1. Summary of CO_2 sources and sinks and their partitioning for all decades since 1960 and for 2008 separately. The uncertainties associated with the various terms are detailed in the Method section of the main text.

	1960-1970	1970-1980	1980-1990	1990-2000	2000-2008	2008
Sources Pg C year^{-1}						
fossil fuel + cement	3.1±0.2	4.7±0.3	5.5±0.3	6.4±0.4	7.7±0.4	8.7±0.5
land use[a]	1.5±0.7	1.3±0.7	1.5±0.7	1.6±0.7	1.4±0.7	1.2±0.7
Sinks Pg C year^{-1}						
atmospheric growth	1.8±0.1	2.7±0.1	3.4±0.1	3.1±0.1	4.1±0.1	3.9±0.1
ocean sink	1.5±0.4	1.7±0.4	2.0±0.4	2.2±0.4	2.3±0.4	2.3±0.4
land sink[b]	1.2±0.9	2.6±1.1	1.8±0.9	2.6±0.9	3.0±0.9	4.7±1.2
residual[b]	0.1±1.3	-1.1±1.4	-0.1±1.3	0.0[d]	-0.3±1.3	-1.1±1.5
Partitioning of total emissions						
atmosphere	0.39±0.07	0.45±0.06	0.48±0.05	0.40±0.04	0.45±0.04	0.39±0.04
ocean	0.33±0.10	0.29±0.08	0.29±0.07	0.28±0.06	0.26±0.05	0.24±0.05
land[c]	0.28±0.12	0.26±0.10	0.23±0.09	0.32±0.07	0.29±0.06	0.37±0.06

[a]Including both the release from deforestation, and cultivation of cropland soils, and the uptake from vegetation regrowth following afforestation, abandonment of agriculture and recovery from logging.
[b]Including only the response to CO_2 increase and climate change. The residual is most likely attributed to unaccounted variability in the land models, with a small part due to uncertainties in LUC (see main text)
[c]Including both the land sink and the residual. The uncertainty is the quadratic sum of the uncertainty in atmosphere and ocean fraction.
[d]The ocean and land sink are corrected to agree with observations over 1990-2000, thus the residual is zero during this time period.

Table S2. References describing the land and ocean models used in this study.

Reference	Model
Ocean models	
Thomas et al. 2008[1]	BEC
Galbraith et al. 2009[2]	BLING
Aumont and Bopp 2006[3]	PISCES
Le Quéré et al. 2007[4]	PISCES-T
Land models	
Sitch et al. 2003[5]; Gerten et al. 2004[6]	LPJ[a]
Friend et al. 2007[7]; Levy et al. 2004[8]	HyLand[a]
Krinner et al. 2005[9]	ORCHIDEE[a]

Woodward et al. 1995[10]; Woodward and Lomas 2004[11]	SDGVM[a]
Cox et al. 2001[12]	TRIFFID[a]

[a]Models also used and compared in Sitch et al. (2008)[13].

2. Uncertainty in land use change (LUC) and its impact on airborne fraction trend

The LUC estimate used here is based on the Houghton (2003)[14] methodology. It is the only published time series of LUC that covers nearly the entire period of our CO_2 budget. This LUC estimate is based on deforestation rates from FAO (2005)[15] statistics. The values presented here are lower than Houghton (2003) due to revised deforestation rates. Other estimates of historical LUC have been based on the SAGE database[16-20] or the HYDE[18-19,21] database as assessed by Hurt et al. (2006)[22]. SAGE uses FAO crop conversion data[15] and did not include conversion of deforestation to pastureland, which accounts for about one third of the total LUC emissions in Houghton's analysis. Neither the HYDE nor SAGE database went beyond year 2000.

LUC estimates based on SAGE only[17,20] showed decreasing LUC between 1958 and 1992 (Figure S1). LUC estimates based on HYDE[19], or a combination of SAGE with HYDE pasture[18] also showed decreasing LUC over the same time period, but of about half the magnitude. The LUC estimate based on FAO deforestation rates used in our study showed a small decrease in LUC from 1958 to 1980, but a small increase during the 1980s. The discrepancy between LUC estimates during the 1980s is well known, and not easy to resolve as trends in deforestation rates are uncertain[23-27].

Other studies have estimated LUC for fixed time periods. Satellite studies provided independent estimates of LUC due to tropical deforestation only, but do not fully capture timber harvest and shifting cultivation. DeFries et al. (2002)[28] estimated LUC of 0.3-0.8 PgC y^{-1} for the 1980s and 0.5-1.4 PgC y^{-1} for the 1990s, but these did not include any legacy emissions due to deforestation that occurred before the 1980s. Achard et al. (2002)[29] estimated LUC of 0.43-0.96 PgC y^{-1} in the 1990s using a proxy for legacy emissions over a 10 year period. Finally, Feanside (2000)[30] provided an estimate of committed deforestation for the tropics of 2.0 PgC y^{-1} and for the globe of 2.4 PgC y^{-1} based on FAO forest statistics and other data for 1981-1990. This later estimate is particularly high as it computes all the carbon that will be released due to a given LUC rather than the annual LUC flux. The time series estimates of LUC shown in Figure S1 are consistent with the LUC estimates based on these other independent studies.

The trend in the fraction of the total CO_2 emissions that remained in the atmosphere (the airborne fraction) was influenced by the uncertainty in LUC estimates. To assess the impact of different LUC estimates, we recalculated the trend in airborne fraction using alternative LUC estimates (Table S3). For all published estimates examined here, the trend in airborne fraction was larger than the one computed by the bookkeeping data. The probability that this trend was above the natural variability was above 0.9, even for a shorter time period. When the LUC estimates were extended to 2008 assuming constant LUC for the last 18 years, the trends remained positive and above the trend computed using the bookkeeping method. Thus we concluded that a positive trend in airborne fraction was likely (66% confidence interval), according to the terminology used by the Intergovernmental Panel on Climate Change. Our assessment considered the p value of 0.9 and the uncertainty in LUC estimates.

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Table S3. Trend in airborne fraction calculated using different estimates for LUC.

Reference	Model	Input data	end year	airborne trend (% y^{-1})	p value[a]
this study	Houghton	FAO deforestation	2008	0.3	0.92
Van Minnen et al. (2009)[19]	IMAGE2	HYDE-default	2000	0.4	0.96
Van Minnen et al. (2009)[19]	IMAGE2	HYDE-pastures	2000	0.5	0.97
McGuire et al. (2001)[17]	IBIS	SAGE	1992	0.7	0.97
McGuire et al. (2001)[17]	HRBM	SAGE	1992	0.7	0.96
McGuire et al. (2001)[17]	LPJ	SAGE	1992	0.9	0.99
McGuire et al. (2001)[17]	TEM	SAGE	1992	0.6	0.94
Piao et al. (2009)[20,b]	ORCHIDEE	SAGE	1992	0.7	0.97
Shevliakova et al. (2009)[18]	LM3V	SAGE/HYDE	1990	1.0	0.999
Shevliakova et al. (2009)[18]	LM3V	HYDE	1990	1.0	0.999

[a]The p value is computed as described in the Methods of the main text and in Canadell et al. (2007)[31].
[b]Estimate after 1992 is not based on historical data and was excluded from this analysis.

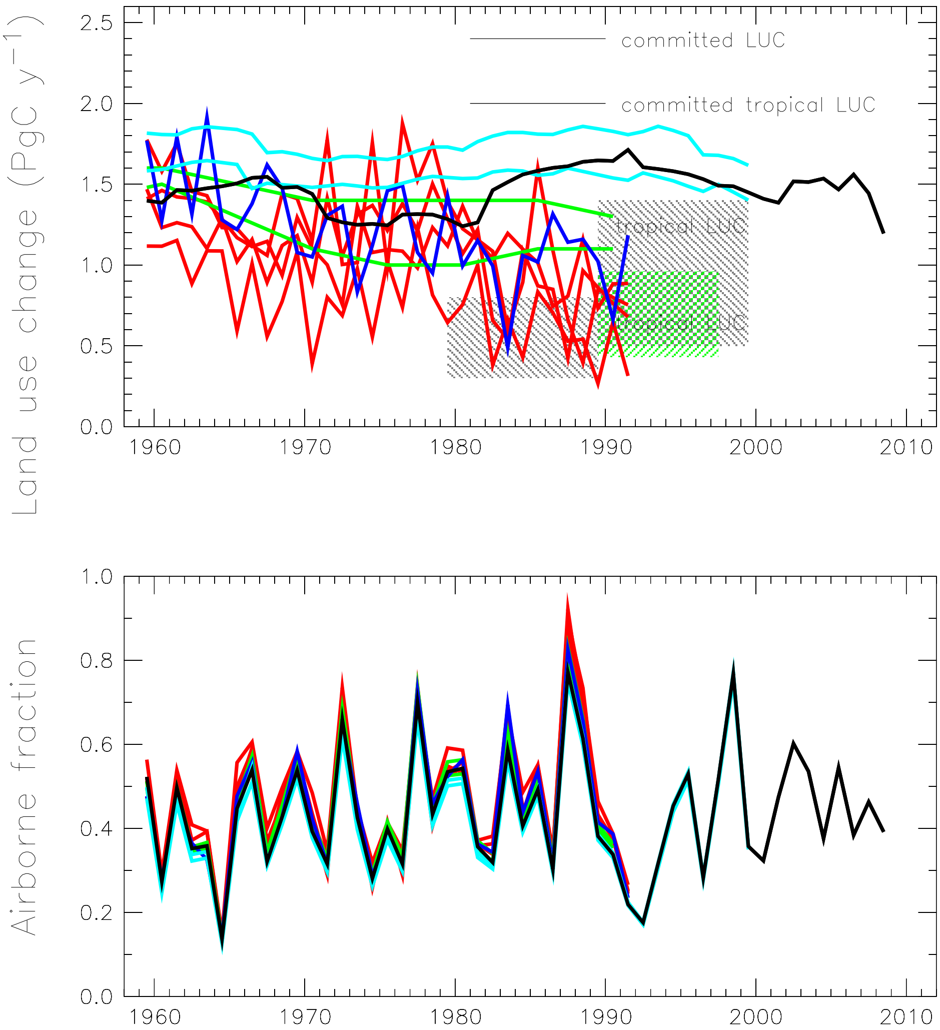

Figure S1. (top) LUC estimates from various sources: (black) this study, (red) four models published in McGuire et al. (2001)[17], (green lines) two models published in Shevliakova et al. (2009)[18], (cyan) two models published in Van Minnen et al. (2009)[19], (blue) Piao et al. (2009)[20]. The gray and green boxes are estimates from DeFries et al. (2002)[28] and Archard et al. (2002)[29], respectively. The committed LUC estimates are from Fearnside (2000)[30]. (Bottom) airborne fraction computed with the various LUC estimates from the top panel.

3. Processes driving the trend in airborne fraction according to models

We assessed the impact of climate variability and climate change on the airborne fraction using a sub-set of our land and ocean models. On land, we used the LPJ, ORCHIDEE, SDGVM, and TRIFFID models (Table S2). In the ocean, we used the BEC, PISCES and PISCES-T models. The land models were forced by increasing CO_2 alone (no changes in climate). The ocean model PISCES-T was also forced by increasing CO_2 alone, whereas PISCES and BEC were forced by changes in climate alone. For the later two models, the effect of increasing CO_2 alone was computed by subtracting the simulation forced by CO_2 and climate from the simulation forced by climate alone. The other model results were used directly.

The CO_2 sinks increased faster in all land and ocean simulations where the models were forced by atmospheric CO_2 alone compared to simulations where atmospheric CO_2 increased and climate changed, except in the SDGVM model which had similar land sink trends in both simulations. The model mean trends are shown in Figure S2. We computed the impact of these trends on the airborne fraction by reconstructing the atmospheric CO_2 based on the total CO_2 emissions minus our mean land and ocean CO_2 sinks. The resulting atmospheric CO_2 is shown in Figure S2(c). As expected, only the simulation where changes in climate are taken into account reproduced the variability in observed atmospheric CO_2. The airborne fraction trend estimated when the models were forced by atmospheric CO_2 alone was -0.8% y^{-1}, and +0.1 % y^{-1} when both atmospheric CO_2 increased and climate changed.

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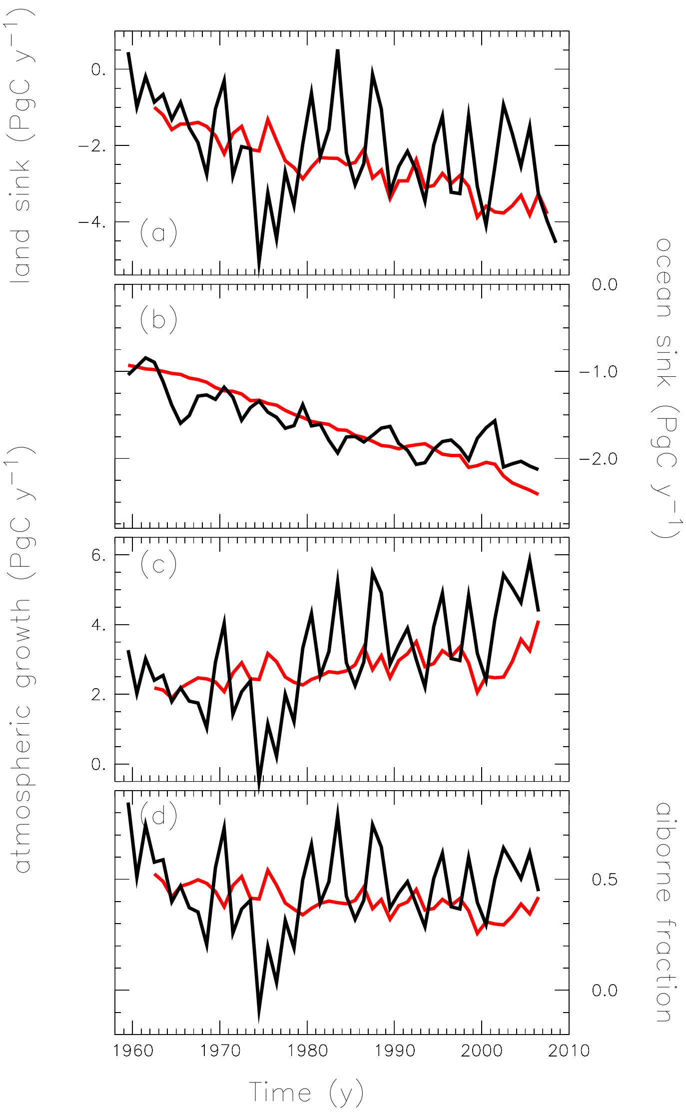

Figure S2. Components of the global CO_2 budget estimated with models forced by increasing CO_2 alone (red curves) and models forced by increasing CO_2 and changes in climate (black curves). Panels (a) and (b) show the land and ocean sinks (PgC y^{-1}). In panel (c), we used the total emissions and subtracted the model estimates of the land and ocean sinks to construct the atmospheric CO_2 inferred by the combination of land and ocean models models (PgC y^{-1}). Panel (d) uses this model-based atmospheric CO_2 to compute the model-based airborne fraction (no units). The model average is shown on all plots.

Using existing model simulations, we tested the impact of different climatic forcing products on the oceanic CO_2 sinks (Figure S3). We isolated the impact of climate alone in simulations forced by NCEP reanalysis[32] (as in the main text), the most recent product of NCEP-2 reanalysis[33], ECMWF reanalysis[34], and wind estimates based on satellite data[35-36]. For all the forcing products tested, the effect of climate variability and climate change was always to reduce the oceanic CO_2 uptake after ~1995 compared to the earlier part of the record. The recent climate-induced trend simulated by the ocean models could be caused by decadal variability, particularly from the tropical Pacific ocean.

Finally, we estimated the impact of climate alone on the ocean CO_2 sink at both pre-industrial atmospheric CO_2 levels and at observed CO_2 levels using the BEC model. The impact of climate induced a trend in the CO_2 sink of 0.083 PgC y^{-1} per decade at comtemporary CO_2 levels, and 0.071 PgC y-1 per decade at pre-industrial CO_2 levels. Thus the loss of buffering capacity in the ocean because of elevated CO_2 led to a larger impact of climate variability and climate change by 15%. This is consistent with the calculation of the increase in Revelle factor of 7% between pre-industrial levels and 1994 of Sabine et al. (2004)[37].

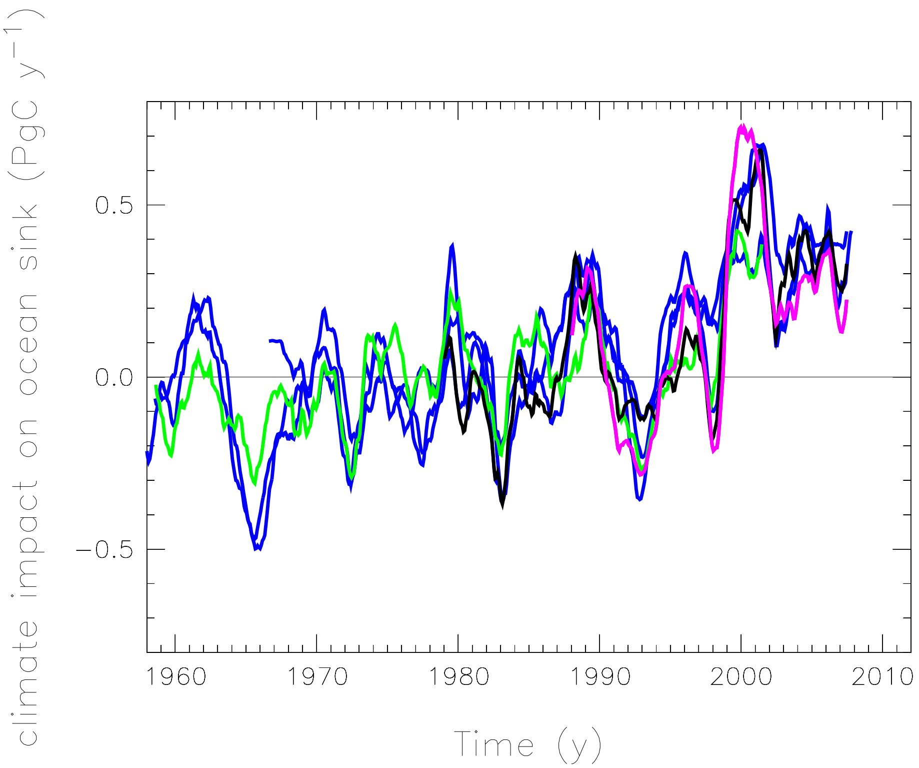

Figure S3. Impact of changes in climate on the ocean sink estimated by ocean models forced by different products (PgC y^{-1}, positive = outgas). The blue curves show results from PISCES-T, PISCES, and BEC forced by NCEP re-analysis. The green curve shows results from PISCES forced by ECMWF reanalysis[ref]. The black curve shows results from PISCES-T forced by NCEP-2 reanalysis[ref]. Finally the purple curve shows results from PISCES-T forced by winds estimated from satellite data[ref]. The 1970-1995 average is removed from all time series to better highlight the trends.

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4. Comparison with atmospheric inverse models

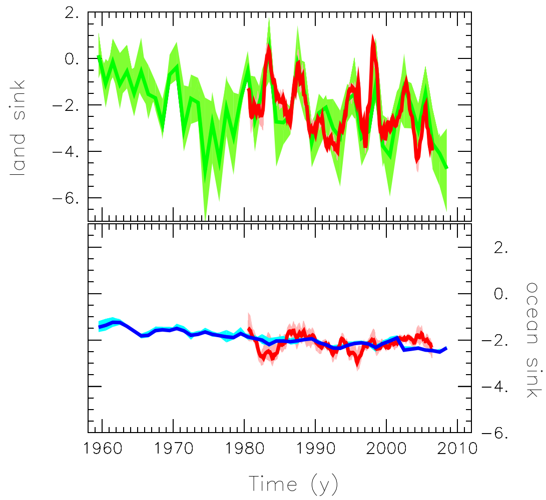

Figure S4. comparison of the land and ocean CO_2 sinks with estimates shown in Figure 2 with estimates from atmospheric inversion methods (red lines)[38]. The net land use estimates shown in Figure 2 (b) is removed from the atmospheric inversion results.

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