

1 Global Carbon Budget 2015

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3 Significant text differences from last year are shown in red

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7 **Abstract**

8 Accurate assessment of anthropogenic carbon dioxide (CO₂) emissions and their redistribution
9 among the atmosphere, ocean, and terrestrial biosphere is important to better understand the
10 global carbon cycle, support the development of climate policies, and project future climate
11 change. Here we describe data sets and a methodology to quantify all major components of the
12 global carbon budget, including their uncertainties, based on the combination of a range of data,
13 algorithms, statistics and model estimates and their interpretation by a broad scientific
14 community. We discuss changes compared to previous estimates, consistency within and among
15 components, alongside methodology and data limitations. CO₂ emissions from fossil fuels and
16 industry (E_{FF}) are based on energy statistics and cement production data, respectively, while
17 emissions from land-use change (E_{LUC}), mainly deforestation, are based on combined evidence
18 from land-cover change data, fire activity associated with deforestation, and models. The global
19 atmospheric CO₂ concentration is measured directly and its rate of growth (G_{ATM}) is computed
20 from the annual changes in concentration. The mean ocean CO₂ sink (S_{OCEAN}) is based on
21 observations from the 1990s, while the annual anomalies and trends are estimated with ocean
22 models. The variability in S_{OCEAN} is evaluated with data products based on surveys of ocean CO₂
23 measurements. The global residual terrestrial CO₂ sink (S_{LAND}) is estimated by the difference of the
24 other terms of the global carbon budget and compared to results of independent Dynamic Global
25 Vegetation Models forced by observed climate, CO₂ and land-cover change (some including
26 nitrogen-carbon interactions). We compare the mean land and ocean fluxes and their variability to
27 estimates from three atmospheric inverse methods for three broad latitude bands. All
28 uncertainties are reported as $\pm 1\sigma$, reflecting the current capacity to characterise the annual
29 estimates of each component of the global carbon budget. For the last decade available (2005-
30 2014), E_{FF} was $9.0 \pm 0.5 \text{ GtC yr}^{-1}$, E_{LUC} $0.9 \pm 0.5 \text{ GtC yr}^{-1}$, G_{ATM} $4.4 \pm 0.1 \text{ GtC yr}^{-1}$, S_{OCEAN} $2.6 \pm 0.5 \text{ GtC}$
31 yr^{-1} , and S_{LAND} $3.0 \pm 0.8 \text{ GtC yr}^{-1}$. For year 2014 alone, E_{FF} grew to $9.8 \pm 0.5 \text{ GtC yr}^{-1}$, 0.6 % above
32 2013, continuing the growth trend in these emissions albeit at a slower rate compared to the
33 average growth of 2.2 % yr^{-1} that took place during 2005-2014. Also for 2014, E_{LUC} was 1.1 ± 0.5
34 GtC yr^{-1} , G_{ATM} was $3.9 \pm 0.2 \text{ GtC yr}^{-1}$, S_{OCEAN} was $2.9 \pm 0.5 \text{ GtC yr}^{-1}$ and S_{LAND} was $4.1 \pm 0.9 \text{ GtC yr}^{-1}$.

1 G_{ATM} was lower in 2014 compared to the past decade (2005-2014), reflecting a larger S_{LAND} for that
2 year. The global atmospheric CO_2 concentration reached 397.15 ± 0.10 ppm averaged over 2014.
3 For 2015, preliminary data indicate that the growth in E_{FF} will be near or slightly below zero, with a
4 projection of -0.6 [range of -1.6 to $+0.5$]%, based on national emissions projections for China and
5 USA, and projections of Gross Domestic Product corrected for recent changes in the carbon
6 intensity of the global economy for the rest of the world. From this projection of E_{FF} and assumed
7 constant E_{LUC} for 2015, cumulative emissions of CO_2 will reach about 555 ± 55 GtC (2035 ± 205
8 Gt CO_2) for 1870-2015, about 75% from E_{FF} and 25% from E_{LUC} . This living data update documents
9 changes in the methods and data sets used in this new carbon budget compared with previous
10 publications of this data set (Le Quéré et al., 2015; 2014; 2013). All observations presented here
11 can be downloaded from the Carbon Dioxide Information Analysis Center (doi:
12 10.3334/CDIAC/GCP_2015).

13 **1 Introduction**

14 The concentration of carbon dioxide (CO_2) in the atmosphere has increased from approximately
15 277 parts per million (ppm) in 1750 (Joos and Spahni, 2008), the beginning of the Industrial Era, to
16 397.15 ppm in 2014 (Dlugokencky and Tans, 2015). Daily averages went above 400 ppm for the
17 first time at Mauna Loa station in May 2013 (Scripps, 2013). This station holds the longest running
18 record of direct measurements of atmospheric CO_2 concentration (Tans and Keeling, 2014). *The*
19 *global monthly average concentration was above 400 ppm in March through May 2015 for the*
20 *first time (Dlugokencky and Tans, 2015; Fig. 1), while at Mauna Loa the seasonally-corrected*
21 *monthly average concentration reached 400 ppm in March 2015 and continued to rise.* The
22 atmospheric CO_2 increase above preindustrial levels was, initially, primarily caused by the release
23 of carbon to the atmosphere from deforestation and other land-use change activities (Ciais et al.,
24 2013). While emissions from fossil fuels started before the Industrial Era, they only became the
25 dominant source of anthropogenic emissions to the atmosphere from around 1920 and their
26 relative share has continued to increase until present. Anthropogenic emissions occur on top of an
27 active natural carbon cycle that circulates carbon between the atmosphere, ocean, and terrestrial
28 biosphere reservoirs on time scales from days to millennia, while exchanges with geologic
29 reservoirs occur at longer timescales (Archer et al., 2009).

30 The global carbon budget presented here refers to the mean, variations, and trends in the
31 perturbation of CO_2 in the atmosphere, referenced to the beginning of the Industrial Era. It

1 quantifies the input of CO₂ to the atmosphere by emissions from human activities, the growth of
 2 CO₂ in the atmosphere, and the resulting changes in the storage of carbon in the land and ocean
 3 reservoirs in response to increasing atmospheric CO₂ levels, climate and variability, and other
 4 anthropogenic and natural changes (Fig. 2). An understanding of this perturbation budget over
 5 time and the underlying variability and trends of the natural carbon cycle are necessary to
 6 understand the response of natural sinks to changes in climate, CO₂ and land-use change drivers,
 7 and the permissible emissions for a given climate stabilization target.

8 The components of the CO₂ budget that are reported annually in this paper include separate
 9 estimates for (1) the CO₂ emissions from fossil fuel combustion and oxidation and cement
 10 production (E_{FF} ; GtC yr⁻¹), (2) the CO₂ emissions resulting from deliberate human activities on land
 11 leading to land-use change (E_{LUC} ; GtC yr⁻¹), (3) the growth rate of CO₂ in the atmosphere (G_{ATM} ; GtC
 12 yr⁻¹), and the uptake of CO₂ by the ‘CO₂ sinks’ in (4) the ocean (S_{OCEAN} ; GtC yr⁻¹) and (5) on land
 13 (S_{LAND} ; GtC yr⁻¹). The CO₂ sinks as defined here include the response of the land and ocean to
 14 elevated CO₂ and changes in climate and other environmental conditions. The global emissions
 15 and their partitioning among the atmosphere, ocean and land are in balance:

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

16 G_{ATM} is usually reported in ppm yr⁻¹, which we convert to units of carbon mass, GtC yr⁻¹, using 1
 17 ppm = 2.12 GtC (Ballantyne et al., 2012; Prather et al., 2012; Table 1). We also include a
 18 quantification of E_{FF} by country, computed with both territorial and consumption based
 19 accounting (see Methods).

20 Equation (1) partly omits two kinds of processes. The first is the net input of CO₂ to the
 21 atmosphere from the chemical oxidation of reactive carbon-containing gases from sources other
 22 than fossil fuels (e.g. fugitive anthropogenic CH₄ emissions, industrial processes, and changes of
 23 biogenic emissions from changes in vegetation, fires, wetlands, etc.), primarily methane (CH₄),
 24 carbon monoxide (CO), and volatile organic compounds such as isoprene and terpene. CO
 25 emissions are currently implicit in E_{FF} while anthropogenic CH₄ emissions are not and thus their
 26 inclusion would result in a small increase in E_{FF} . The second is the anthropogenic perturbation to
 27 carbon cycling in terrestrial freshwaters, estuaries, and coastal areas, that modifies lateral fluxes
 28 from land ecosystems to the open ocean, the evasion CO₂ flux from rivers, lakes and estuaries to
 29 the atmosphere, and the net air-sea anthropogenic CO₂ flux of coastal areas (Regnier et al., 2013).
 30 The inclusion of freshwater fluxes of anthropogenic CO₂ would affect the estimates of, and

1 partitioning between, S_{LAND} and S_{OCEAN} in Eq. (1) in complementary ways, but would not affect the
2 other terms. These flows are omitted in absence of annual information on the natural versus
3 anthropogenic perturbation terms of these loops of the carbon cycle, and they are discussed in
4 Section 2.7.

5 The CO₂ budget has been assessed by the Intergovernmental Panel on Climate Change (IPCC) in all
6 assessment reports (Ciais et al., 2013; Denman et al., 2007; Prentice et al., 2001; Schimel et al.,
7 1995; Watson et al., 1990), and by others (e.g. Ballantyne et al., 2012). These assessments
8 included budget estimates for the decades of the 1980s, 1990s (Denman et al., 2007) and, most
9 recently, the period 2002-2011 (Ciais et al., 2013). The IPCC methodology has been adapted and
10 used by the Global Carbon Project (GCP, www.globalcarbonproject.org), which has coordinated a
11 cooperative community effort for the annual publication of global carbon budgets up to year 2005
12 (Raupach et al., 2007; including fossil emissions only), year 2006 (Canadell et al., 2007), year 2007
13 (published online; GCP, 2007), year 2008 (Le Quéré et al., 2009), year 2009 (Friedlingstein et al.,
14 2010), year 2010 (Peters et al., 2012b), year 2012 (Le Quéré et al., 2013; Peters et al., 2013), year
15 2013 (Le Quéré et al., 2014), and most recently year 2014 (Friedlingstein et al., 2014; Le Quéré et
16 al., 2015), where the carbon budget year refers to the initial year of publication. Each of these
17 papers updated previous estimates with the latest available information for the entire time series.
18 From 2008, these publications projected fossil fuel emissions for one additional year using the
19 projected World Gross Domestic Product and estimated trends in the carbon intensity of the
20 global economy.

21 We adopt a range of ± 1 standard deviation (σ) to report the uncertainties in our estimates,
22 representing a likelihood of 68% that the true value will be within the provided range if the errors
23 have a Gaussian distribution. This choice reflects the difficulty of characterising the uncertainty in
24 the CO₂ fluxes between the atmosphere and the ocean and land reservoirs individually,
25 particularly on an annual basis, as well as the difficulty of updating the CO₂ emissions from land-
26 use change. A likelihood of 68% provides an indication of our current capability to quantify each
27 term and its uncertainty given the available information. For comparison, the Fifth Assessment
28 Report of the IPCC (AR5) generally reported a likelihood of 90% for large data sets whose
29 uncertainty is well characterised, or for long time intervals less affected by year-to-year variability.
30 Our 68% uncertainty value is near the 66% which the IPCC characterises as ‘likely’ for values falling
31 into the $\pm 1\sigma$ interval. The uncertainties reported here combine statistical analysis of the

1 underlying data and expert judgement of the likelihood of results lying outside this range. The
2 limitations of current information are discussed in the paper **and have been examined in detail**
3 **elsewhere (Ballantyne et al., 2015).**

4 All quantities are presented in units of gigatonnes of carbon (GtC, 10^{15} gC), which is the same as
5 petagrams of carbon (PgC; Table 1). Units of gigatonnes of CO₂ (or billion tonnes of CO₂) used in
6 policy are equal to 3.664 multiplied by the value in units of GtC.

7 This paper provides a detailed description of the data sets and methodology used to compute the
8 global carbon budget estimates for the period preindustrial (1750) to 2014 and in more detail for
9 the period 1959 to 2014. We also provide decadal averages starting in 1960 including the last
10 decade (2005-2014), results for the year 2014, and a projection of E_{FF} for year 2015. Finally we
11 provide cumulative emissions from fossil fuels and land-use change since year 1750, the
12 preindustrial period, and since year 1870, the reference year for the cumulative carbon estimate
13 used by the IPCC (AR5) based on the availability of global temperature data (Stocker et al., 2013).
14 This paper will be updated every year using the format of ‘living data’ to keep a record of budget
15 versions and the changes in new data, revision of data, and changes in methodology that lead to
16 changes in estimates of the carbon budget. Additional materials associated with the release of
17 each new version will be posted at the Global Carbon Project (GCP) website
18 (<http://www.globalcarbonproject.org/carbonbudget>). Data associated with this release are also
19 available through the Global Carbon Atlas (<http://www.globalcarbonatlas.org>). With this
20 approach, we aim to provide the highest transparency and traceability in the reporting of CO₂, the
21 key driver of climate change.

22 **2 Methods**

23 Multiple organizations and research groups around the world generated the original
24 measurements and data used to complete the global carbon budget. The effort presented here is
25 thus mainly one of synthesis, where results from individual groups are collated, analysed and
26 evaluated for consistency. We facilitate access to original data with the understanding that
27 primary data sets will be referenced in future work (See Table 2 for ‘How to cite’ the data sets).
28 Descriptions of the measurements, models, and methodologies follow below and in depth
29 descriptions of each component are described elsewhere (e.g. Andres et al., 2012; Houghton et
30 al., 2012).

1 This is the tenth version of the ‘global carbon budget’ (see Introduction for details) and the fourth
2 revised version of the ‘global carbon budget living data update’. It is an update of Le Quéré et al.
3 (2015), including data to year 2014 (inclusive) and a projection for fossil fuel emissions for year
4 2015. The main changes from Le Quéré et al. (2015) are: (1) the use of national emissions for E_{FF}
5 from the United Nations Framework Convention on Climate Change (UNFCCC) where available, (2)
6 the projection of E_{FF} for 2015 is based on national emissions projections for China and USA, and
7 gross domestic product corrected for recent changes in the carbon intensity of the global
8 economy for the rest of the world, and (3) we apply minimum criteria of realism to select ocean
9 data products and process models. The main methodological differences between annual carbon
10 budgets are summarised in Table 3.

11 **2.1 CO₂ emissions from fossil fuels and industry (E_{FF})**

12 **2.1.1 Emissions from fossil fuels and industry and their uncertainty**

13 The calculation of global and national CO₂ emissions from fossil fuels, including gas flaring and
14 cement production (E_{FF}), relies primarily on energy consumption data, specifically data on
15 hydrocarbon fuels, collated and archived by several organisations (Andres et al., 2012). These
16 include the Carbon Dioxide Information Analysis Center (CDIAC), the International Energy Agency
17 (IEA), the United Nations (UN), the United States Department of Energy (DoE) Energy Information
18 Administration (EIA), and more recently also the Planbureau voor de Leefomgeving (PBL)
19 Netherlands Environmental Assessment Agency. Where available, we use national emissions
20 estimated by the countries themselves and reported to the UNFCCC for the period 1990-2012 (42
21 countries). We assume that national emissions reported to the UNFCCC are the most accurate
22 because national experts have access to additional and country-specific information, and because
23 these emission estimates are periodically audited for each country through an established
24 international methodology overseen by the UNFCCC. We also use global and national emissions
25 estimated by CDIAC (Boden et al., 2013). The CDIAC emission estimates are the only data set that
26 extends back in time to 1751 with consistent and well-documented emissions from fossil fuels,
27 cement production, and gas flaring for all countries and their uncertainty (Andres et al., 2014;
28 Andres et al., 2012; Andres et al., 1999); this makes the data set a unique resource for research of
29 the carbon cycle during the fossil fuel era.

1 The global emissions presented here are from CDIAC’s analysis, which provides an internally-
2 consistent global estimate including bunker fuels, minimising the effects of lower-quality energy
3 trade data. Thus the comparison of global emissions with previous annual carbon budgets is not
4 influenced by the use data from UNFCCC national reports.

5 During the period 1959-2011, the emissions from fossil fuels estimated by CDIAC are based
6 primarily on energy data provided by the UN Statistics Division (UN, 2014a; b; Table 4). When
7 necessary, fuel masses/volumes are converted to fuel energy content using coefficients provided
8 by the UN and then to CO₂ emissions using conversion factors that take into account the
9 relationship between carbon content and energy (heat) content of the different fuel types (coal,
10 oil, gas, gas flaring) and the combustion efficiency (to account, for example, for soot left in the
11 combustor or fuel otherwise lost or discharged without oxidation). Most data on energy
12 consumption and fuel quality (carbon content and heat content) are available at the country level
13 (UN, 2014a). In general, CO₂ emissions for equivalent primary energy consumption are about 30%
14 higher for coal compared to oil, and 70% higher for coal compared to natural gas (Marland et al.,
15 2007). All estimated fossil fuel emissions are based on the mass flows of carbon and assume that
16 the fossil carbon emitted as CO or CH₄ will soon be oxidized to CO₂ in the atmosphere and can be
17 accounted for with CO₂ emissions (see Section 2.7).

18 Our emissions totals for the UNFCCC-reporting countries were recorded as in the UNFCCC
19 submissions, which have a slightly larger system boundary than CDIAC. Additional emissions come
20 from carbonates other than in cement manufacture, and thus UNFCCC totals will be to be slightly
21 higher than CDIAC totals in general, although there are multiple sources for differences. We use
22 the CDIAC method to report emissions by fuel type (e.g. all coal oxidation is reported under ‘coal’,
23 regardless of whether oxidation results from combustion as an energy source), which differs
24 slightly from UNFCCC.

25 For the most recent 2-3 years when the UNFCCC estimates and UN statistics used by CDIAC are
26 not yet available (or there was insufficient time to process and verify them), we generated
27 preliminary estimates based on the BP annual energy review by applying the growth rates of
28 energy consumption (coal, oil, gas) for 2013-2014 to the UNFCCC national emissions in 2012, and
29 for 2012-2014 for the CDIAC national and global emissions in 2011 (BP, 2015). BP's sources for
30 energy statistics overlap with those of the UN data, but are compiled more rapidly from about 70
31 countries covering about 96% of global emissions. We use the BP values only for the year-to-year

1 rate of change, because the rates of change are less uncertain than the absolute values and to
2 avoid discontinuities in the time-series when linking the UN-based data with the BP data. These
3 preliminary estimates are replaced by the more complete UNFCCC or CDIAC data based on UN
4 statistics when they become available. Past experience and work by others (Andres et al., 2014;
5 Myhre et al., 2009) shows that projections based on the BP rate of change are within the
6 uncertainty provided (see Sect. 3.2 and Supplementary Information from Peters et al., 2013).

7 Estimates of emissions from cement production by CDIAC are based on data on growth rates of
8 cement production from the US Geological Survey up to year 2013 (van Oss, 2013), and up to
9 2014 for the top 18 countries (representing 85% of global production; USGS, 2015). For countries
10 without data in 2014 we use the 2013 values (zero growth). Some fraction of the CaO and MgO in
11 cement is returned to the carbonate form during cement weathering but this is generally
12 regarded to be small and is ignored here.

13 Estimates of emissions from gas flaring by CDIAC are calculated in a similar manner as those from
14 solid, liquid, and gaseous fuels, and rely on the UN Energy Statistics to supply the amount of flared
15 or vented fuel. For emission years 2012-2014, flaring is assumed constant from 2011 (emission
16 year) UN-based data. The basic data on gas flaring report atmospheric losses during petroleum
17 production and processing that have large uncertainty and do not distinguish between gas that is
18 flared as CO₂ or vented as CH₄. Fugitive emissions of CH₄ from the so-called upstream sector (e.g.,
19 coal mining and natural gas distribution) are not included in the accounts of CO₂ emissions except
20 to the extent that they are captured in the UN energy data and counted as gas 'flared or lost'.

21 The published CDIAC data set includes 250 countries and regions. This expanded list includes
22 countries that no longer exist, such as the USSR and East Pakistan. For the carbon budget, we
23 reduce the list to 216 countries by reallocating emissions to the currently defined territories. This
24 involved both aggregation and disaggregation, and does not change global emissions. Examples of
25 aggregation include merging East and West Germany to the currently defined Germany. Examples
26 of disaggregation include reallocating the emissions from former USSR to the resulting
27 independent countries. For disaggregation, we use the emission shares when the current territory
28 first appeared. The disaggregated estimates should be treated with care when examining
29 countries' emissions trends prior to their disaggregation. For the most recent years, 2012-2014,
30 the BP statistics are more aggregated, but we retain the detail of CDIAC by applying the growth
31 rates of each aggregated region in the BP data set to its constituent individual countries in CDIAC.

1 Estimates of CO₂ emissions show that the global total of emissions is not equal to the sum of
2 emissions from all countries. This is largely attributable to emissions that occur in international
3 territory, in particular the combustion of fuels used in international shipping and aviation (bunker
4 fuels), where the emissions are included in the global totals but are not attributed to individual
5 countries. In practice, the emissions from international bunker fuels are calculated based on
6 where the fuels were loaded, but they are not included with national emissions estimates. Other
7 differences occur because globally the sum of imports in all countries is not equal to the sum of
8 exports and because of differing treatment of oxidation of non-fuel uses of hydrocarbons (e.g. as
9 solvents, lubricants, feedstocks, etc.), and changes in stock (Andres et al., 2012).

10 The uncertainty of the annual emissions from fossil fuels and industry for the globe has been
11 estimated at $\pm 5\%$ (scaled down from the published $\pm 10\%$ at $\pm 2\sigma$ to the use of $\pm 1\sigma$ bounds
12 reported here; Andres et al., 2012). This is consistent with a more detailed recent analysis of
13 uncertainty of $\pm 8.4\%$ at $\pm 2\sigma$ (Andres et al., 2014) and at the high-end of the range of $\pm 5\text{-}10\%$ at
14 $\pm 2\sigma$ reported by Ballantyne et al. (2015). This includes an assessment of uncertainties in the
15 amounts of fuel consumed, the carbon and heat contents of fuels, and the combustion efficiency.
16 While in the budget we consider a fixed uncertainty of $\pm 5\%$ for all years, in reality the uncertainty,
17 as a percentage of the emissions, is growing with time because of the larger share of global
18 emissions from non-Annex B countries (emerging economies and developing countries) with less
19 precise statistical systems (Marland et al., 2009). For example, the uncertainty in Chinese
20 emissions has been estimated at around $\pm 10\%$ (for $\pm 1\sigma$; Gregg et al., 2008), and important
21 potential biases have been identified suggesting China's emissions could be overestimated in
22 published studies (Liu et al. 2015). Generally, emissions from mature economies with good
23 statistical bases have an uncertainty of only a few per cent (Marland, 2008). Further research is
24 needed before we can quantify the time evolution of the uncertainty, and its temporal error
25 correlation structure. We note that even if they are presented as 1σ estimates, uncertainties of
26 emissions are likely to be mainly country-specific systematic errors related to underlying biases of
27 energy statistics and to the accounting method used by each country. We assign a medium
28 confidence to the results presented here because they are based on indirect estimates of
29 emissions using energy data (Durant et al., 2010). There is only limited and indirect evidence for
30 emissions, although there is a high agreement among the available estimates within the given
31 uncertainty (Andres et al., 2014; Andres et al., 2012), and emission estimates are consistent with a

1 range of other observations (Ciais et al., 2013), even though their regional and national
2 partitioning is more uncertain (Francey et al., 2013).

3 **2.1.2 Emissions embodied in goods and services**

4 National emission inventories take a territorial (production) perspective and ‘include greenhouse
5 gas emissions and removals taking place within national territory and offshore areas over which
6 the country has jurisdiction’ (Rypdal et al., 2006). That is, emissions are allocated to the country
7 where and when the emissions actually occur. The territorial emission inventory of an individual
8 country does not include the emissions from the production of goods and services produced in
9 other countries (e.g. food and clothes) that are used for consumption. Consumption-based
10 emission inventories for an individual country is another attribution point of view that allocates
11 global emissions to products that are consumed within a country, and are conceptually calculated
12 as the territorial emissions minus the ‘embedded’ territorial emissions to produce exported
13 products plus the emissions in other countries to produce imported products (Consumption =
14 Territorial – Exports + Imports). The difference between the territorial- and consumption-based
15 emission inventories is the net transfer (exports minus imports) of emissions from the production
16 of internationally traded products. Consumption-based emission attribution results (e.g. Davis and
17 Caldeira, 2010) provide additional information to territorial-based emissions that can be used to
18 understand emission drivers (Hertwich and Peters, 2009), quantify emission (virtual) transfers by
19 the trade of products between countries (Peters et al., 2011b) and potentially design more
20 effective and efficient climate policy (Peters and Hertwich, 2008).

21 We estimate consumption-based emissions by enumerating the global supply chain using a global
22 model of the economic relationships between economic sectors within and between every
23 country (Andrew and Peters, 2013; Peters et al., 2011a). Due to availability of the input data,
24 detailed estimates are made for the years 1997, 2001, 2004, 2007, and 2011 (using the
25 methodology of Peters et al., 2011b) using economic and trade data from the Global Trade and
26 Analysis Project **version 9 (GTAP; Narayanan et al., 2015)**. The results cover 57 sectors and **140**
27 countries and regions. The results are extended into an annual time-series from 1990 to the latest
28 year of the fossil fuel emissions or GDP data (2013 in this budget), using Gross Domestic Product
29 (GDP) data by expenditure in current exchange rate of US dollars (USD; from the UN National
30 Accounts main Aggregates database; UN, 2014c) and time series of trade data from GTAP (based
31 on the methodology in Peters et al., 2011b).

1 The detailed consumption-based estimates for 2004, 2007 and 2011 and time series
2 approximation from 1990-2013 are based on an updated version of the GTAP database
3 (Narayanan et al., 2015). We estimate the sector level CO₂ emissions using our own calculations
4 based on the GTAP data and methodology, include flaring and cement emissions from CDIAC, and
5 then scale the national totals (excluding bunker fuels) to match the CDIAC estimates from the
6 most recent carbon budget. We do not include international transportation in our estimates of
7 national totals, but include them in the global total. The time-series of trade data provided by
8 GTAP covers the period 1995-2011 and our methodology uses the trade shares as this data set.
9 For the period 1990-1994 we assume the trade shares of 1995, while for 2012 and 2013 we
10 assume the trade shares of 2011.

11 Comprehensive analysis of the uncertainty of consumption emissions accounts is still lacking in
12 the literature, although several analyses of components of this uncertainty have been made (e.g.
13 Dietzenbacher et al., 2012; Inomata and Owen, 2014; Karstensen et al., 2015; Moran and Wood,
14 2014). For this reason we do not provide, we do not provide an uncertainty estimate for these
15 emissions, but based on model comparisons and sensitivity analysis, they are unlikely to be larger
16 than for the territorial emission estimates (Peters et al., 2012a). Uncertainty is expected to
17 increase for more detailed results, and to decrease with aggregation (Peters et al., 2011b; e.g. the
18 results for Annex B countries will be more accurate than the sector results for an individual
19 country).

20 The consumption-based emissions attribution method considers the CO₂ emitted to the
21 atmosphere in the production of products, but not the trade in fossil fuels (coal, oil, gas). It is also
22 possible to account for the carbon trade in fossil fuels (Davis et al., 2011), but we do not present
23 those data here. Peters et al. (2012a) additionally considered trade in biomass.

24 The consumption data do not modify the global average terms in Eq. (1), but are relevant to the
25 anthropogenic carbon cycle as they reflect the trade-driven movement of emissions across the
26 Earth's surface in response to human activities. Furthermore, if national and international climate
27 policies continue to develop in an un-harmonised way, then the trends reflected in these data will
28 need to be accommodated by those developing policies.

1 2.1.3 Growth rate in emissions

2 We report the annual growth rate in emissions for adjacent years (in percent per year) by
 3 calculating the difference between the two years and then comparing to the emissions in the first
 4 year: $\left[\frac{E_{FF}(t_{0+1}) - E_{FF}(t_0)}{E_{FF}(t_0)} \right] \times \%yr^{-1}$. This is the simplest method to characterise a one-year growth
 5 compared to the previous year and is widely used. We apply a leap-year adjustment to ensure
 6 valid interpretations of annual growth rates. This affects the growth rate by about $0.3\% yr^{-1}$ ($\frac{1}{365}$)
 7 and causes growth rates to go up approximately 0.3% if the first year is a leap year and down 0.3%
 8 if the second year is a leap year.

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

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

11 Here we calculate relative growth rates in emissions for multi-year periods (e.g. a decade) by
 12 fitting a linear trend to $\ln(E_{FF})$ in Eq. (2), reported in percent per year. We fit the logarithm of E_{FF}
 13 rather than E_{FF} directly because this method ensures that computed growth rates satisfy Eq. (6).
 14 This method differs from previous papers (Canadell et al., 2007; Le Quéré et al., 2009; Raupach et
 15 al., 2007) that computed the fit to E_{FF} and divided by average E_{FF} directly, but the difference is very
 16 small (<0.05%) in the case of E_{FF} .

17 2.1.4 Emissions projections

18 Energy statistics from BP are normally available around June for the previous year. **To gain insight**
 19 **on emission trends for the current year (2015), we provide an assessment of global emissions for**
 20 **E_{FF} by combining individual assessments of emissions for China and the USA (the two biggest**
 21 **emitting countries), and the rest of the world.**

22 **We specifically estimate emissions in China because the evidence suggests a departure from the**
 23 **long-term trends in the carbon intensity of the economy used in emissions projections in previous**
 24 **global carbon budgets (e.g. Le Quéré et al. 2015), resulting from significant drops in industrial**
 25 **production against continued growth in economic output. This departure could be temporary**
 26 **(Jackson et al., in press). Our 2015 estimate for China uses: (1) apparent consumption of coal for**
 27 **January to August estimated using production data from the National Bureau of Statistics (2015b),**

1 imports and exports of coal from China Customs Statistics (General Administration of Customs of
2 the People’s Republic of China, 2015a, b), and from partial data on stock changes from industry
3 sources (China Coal Industry Association, 2015; China Coal Resource, 2015), (2) apparent
4 consumption of oil and gas for January to June from the National Energy Administration (2015),
5 and (3) production of cement reported for January to August (National Bureau of Statistics of
6 China, 2015b). Using these data, we estimate the change in emissions for the corresponding
7 months in 2015 compared to 2014 assuming constant emission factors. We then assume that the
8 relative changes during the first 6-8 months will persist throughout the year. The main sources of
9 uncertainty are from the incomplete data on stock changes, the carbon content of coal and the
10 assumption of persistent behaviour for the rest of 2015. These are discussed further in section
11 3.2.1. We tested our new method using data available in October 2014 to make a 2014 projection
12 of coal consumption and cement production, both of which changed substantially in 2014. For the
13 apparent consumption of coal we would have projected a change of –3.2% in coal use for 2014,
14 compared to –2.9% reported by NBS in February 2015, while for the production of cement we
15 would have projected a change of +3.5%, compared to a realised change of +2.3%. In both cases,
16 the projection is consistent with the sign of the realised change. This new method should be more
17 reliable as it is based on actual data, even if they are preliminary. Note that the growth rates we
18 project for China are unaffected by recent upwards revisions of Chinese energy consumption statistics
19 (National Bureau of Statistics of China, 2015a), as all data used here dates from after the revised period.
20 The revisions do however affect the absolute value of the time series up to 2013, and hence the absolute
21 value for 2015 extrapolated from that time series using projected growth rates. Further, because the
22 revisions will increase China’s share of total global emissions, the projected growth rate of global emissions
23 will also be affected slightly. This effect is discussed in the results section.

24 For the USA, we use the forecast of the U.S. Energy Information Administration (EIA) ‘Short-term
25 energy outlook’ (October 2015) for emissions from fossil fuels. This is based on an energy
26 forecasting model which is revised monthly, and takes into account heating-degree days,
27 household expenditures by fuel type, energy markets, policies, and other effects. We combine this
28 with our estimate of emissions from cement production using the monthly U.S. cement data from
29 USGS for January-July, assuming changes in cement production over the first seven months apply
30 throughout the year. We estimate an uncertainty range using the revisions of historical October
31 forecasts made by the EIA one year later. These were less than 2% during 2009-2014 (when a

1 forecast was done), except for 2011 when it was -4.0% . We thus use a conservative uncertainty
2 range of -4.0% to $+1.8\%$ around the central forecast.

3 For the rest of the world, we use the close relationship between the growth in GDP and the
4 growth in emissions (Raupach et al., 2007) to project emissions for the current year. This is based
5 on the so-called Kaya identity (also called IPAT identity, the acronym standing for human impact
6 (I) on the environment, which is equal to the product of P= population, A= affluence, T=
7 technology), whereby E_{FF} (GtC yr^{-1}) is decomposed by the product of GDP (USD yr^{-1}) and the fossil
8 fuel carbon intensity of the economy (I_{FF} ; GtC USD^{-1}) as follows:

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

9 Such product-rule decomposition identities imply that the relative growth rates of the multiplied
10 quantities are additive. Taking a time derivative of Equation (3) gives:

$$\frac{dE_{FF}}{dt} = \frac{d(GDP \times I_{FF})}{dt} \quad (4)$$

11 and applying the rules of calculus:

$$\frac{dE_{FF}}{dt} = \frac{dGDP}{dt} \times I_{FF} + GDP \times \frac{dI_{FF}}{dt} \quad (5)$$

12 finally, dividing (5) by (3) gives :

$$\frac{1}{E_{FF}} \frac{dE_{FF}}{dt} = \frac{1}{GDP} \frac{dGDP}{dt} + \frac{1}{I_{FF}} \frac{dI_{FF}}{dt} \quad (6)$$

13
14 where the left hand term is the relative growth rate of E_{FF} , and the right hand terms are the
15 relative growth rates of GDP and I_{FF} , respectively, which can simply be added linearly to give
16 overall growth rate. The growth rates are reported in percent by multiplying each term by 100. As
17 preliminary estimates of annual change in GDP are made well before the end of a calendar year,
18 making assumptions on the growth rate of I_{FF} allows us to make projections of the annual change
19 in CO_2 emissions well before the end of a calendar year. The I_{FF} is based on GDP in constant PPP
20 (purchasing power parity) from the IEA (2014) up to 2012 (IEA/OECD, 2014) and extended using
21 the IMF growth rates for 2013 and 2014 (IMF, 2015). Experience of the past year has highlighted
22 that the interannual variability in I_{FF} is the largest source of uncertainty in the GDP-based
23 emissions projections. We thus use the standard deviation of the annual I_{FF} for the period 2005-

1 2014 as a measure of uncertainty, reflecting a $\pm 1\sigma$ as in the rest of the carbon budget. This is
2 $\pm 1.4\% \text{ yr}^{-1}$ for the rest of the world (global emissions minus China and USA).

3 The 2015 projection for the world is made of the sum of the projections for China, USA, and the
4 rest. The uncertainty is added quadratically among the three regions. The uncertainty here
5 reflects the best of our expert opinion.

6 **2.2 CO₂ emissions from land use, land-use change and forestry (E_{LUC})**

7 Land-use change emissions reported here (E_{LUC}) include CO₂ fluxes from deforestation,
8 afforestation, logging (forest degradation and harvest activity), shifting cultivation (cycle of cutting
9 forest for agriculture, then abandoning), and regrowth of forests following wood harvest or
10 abandonment of agriculture. Only some land management activities (Table 5) are included in our
11 land-use change emissions estimates (e.g. emissions or sinks related to management and
12 management changes of established pasture and croplands are not included). Some of these
13 activities lead to emissions of CO₂ to the atmosphere, while others lead to CO₂ sinks. E_{LUC} is the
14 net sum of all anthropogenic activities considered. Our annual estimate for 1959-2010 is from a
15 bookkeeping method (Sect. 2.2.1) primarily based on net forest area change and biomass data
16 from the Forest Resource Assessment (FRA) of the Food and Agriculture Organisation (FAO) which
17 is only available at intervals of five years. We use the FAO FRA 2010 here (Houghton et al., 2012).
18 Inter-annual variability in emissions due to deforestation and degradation have been coarsely
19 estimated from satellite-based fire activity in tropical forest areas (Section 2.2.2; Giglio et al.,
20 2013; van der Werf et al., 2010). The bookkeeping method is used to quantify the E_{LUC} over the
21 time period of the available data, and the satellite-based deforestation fire information to
22 incorporate interannual variability (E_{LUC} flux annual anomalies) from tropical deforestation fires.
23 The satellite-based deforestation and degradation fire emissions estimates are available for years
24 1997-2014. We calculate the global annual anomaly in deforestation and degradation fire
25 emissions in tropical forest regions for each year, compared to the 1997-2010 period, and add this
26 annual flux anomaly to the E_{LUC} estimated using the bookkeeping method that is available up to
27 2010 only and assumed constant at the 2010 value during the period 2011-2014. We thus assume
28 that all land management activities apart from deforestation and degradation do not vary
29 significantly on a year-to-year basis. Other sources of interannual variability (e.g. the impact of
30 climate variability on regrowth fluxes) are accounted for in S_{LAND}. In addition, we use results from

1 Dynamic Global Vegetation Models (see Section 2.2.3 and Table 6) that calculate net land-use
2 change CO₂ emissions in response to land-cover change reconstructions prescribed to each model,
3 to help quantify the uncertainty in E_{LUC}, and to explore the consistency of our understanding. The
4 three methods are described below, and differences are discussed in Section 3.2.

5 **2.2.1 Bookkeeping method**

6 Land-use change CO₂ emissions are calculated by a bookkeeping method approach (Houghton,
7 2003) that keeps track of the carbon stored in vegetation and soils before deforestation or other
8 land-use change, and the changes in forest age classes, or cohorts, of disturbed lands after land-
9 use change including possible forest regrowth after deforestation. It tracks the CO₂ emitted to the
10 atmosphere immediately during deforestation, and over time due to the follow-up decay of soil
11 and vegetation carbon in different pools, including wood products pools after logging and
12 deforestation. It also tracks the regrowth of vegetation and associated build-up of soil carbon
13 pools after land-use change. It considers transitions between forests, pastures and cropland;
14 shifting cultivation; degradation of forests where a fraction of the trees is removed; abandonment
15 of agricultural land; and forest management such as wood harvest and, in the USA, fire
16 management. In addition to tracking logging debris on the forest floor, the bookkeeping method
17 tracks the fate of carbon contained in harvested wood products that is eventually emitted back to
18 the atmosphere as CO₂, although a detailed treatment of the lifetime in each product pool is not
19 performed (Earles et al., 2012). Harvested wood products are partitioned into three pools with
20 different turnover times. All fuel-wood is assumed burnt in the year of harvest (1.0 yr⁻¹). Pulp and
21 paper products are oxidized at a rate of 0.1 yr⁻¹, timber is assumed to be oxidized at a rate of 0.01
22 yr⁻¹, and elemental carbon decays at 0.001 yr⁻¹. The general assumptions about partitioning wood
23 products among these pools are based on national harvest data (Houghton, 2003).

24 The primary land-cover change and biomass data for the bookkeeping method analysis is the
25 Forest Resource Assessment of the FAO which provides statistics on forest-cover change and
26 management at intervals of five years (FAO, 2010). The data is based on countries' self-reporting
27 some of which include satellite data in more recent assessments (Table 4). Changes in land cover
28 other than forest are based on annual, national changes in cropland and pasture areas reported
29 by the FAO Statistics Division (FAOSTAT, 2010). Land-use change country data are aggregated by
30 regions. The carbon stocks on land (biomass and soils), and their response functions subsequent
31 to land-use change, are based on FAO data averages per land cover type, per biome and per

1 region. Similar results were obtained using forest biomass carbon density based on satellite data
2 (Baccini et al., 2012). The bookkeeping method does not include land ecosystems' transient
3 response to changes in climate, atmospheric CO₂ and other environmental factors, but the
4 growth/decay curves are based on contemporary data that will implicitly reflect the effects of CO₂
5 and climate at that time. Results from the bookkeeping method are available from 1850 to 2010.

6 **2.2.2 Fire-based interannual variability in E_{LUC}**

7 Land-use change associated CO₂ emissions calculated from satellite-based fire activity in tropical
8 forest areas (van der Werf et al., 2010) provide information on emissions due to tropical
9 deforestation and degradation that are complementary to the bookkeeping approach. They do
10 not provide a direct estimate of E_{LUC} as they do not include non-combustion processes such as
11 respiration, wood harvest, wood products or forest regrowth. Legacy emissions such as
12 decomposition from on-ground debris and soils are not included in this method either. However,
13 fire estimates provide some insight in the year-to-year variations in the sub-component of the
14 total E_{LUC} flux that result from immediate CO₂ emissions during deforestation caused, for example,
15 by the interactions between climate and human activity (e.g. there is more burning and clearing of
16 forests in dry years) that are not represented by other methods. The 'deforestation fire emissions'
17 assume an important role of fire in removing biomass in the deforestation process, and thus can
18 be used to infer gross instantaneous CO₂ emissions from deforestation using satellite-derived data
19 on fire activity in regions with active deforestation. The method requires information on the
20 fraction of total area burned associated with deforestation versus other types of fires, and this
21 information can be merged with information on biomass stocks and the fraction of the biomass
22 lost in a deforestation fire to estimate CO₂ emissions. The satellite-based deforestation fire
23 emissions are limited to the tropics, where fires result mainly from human activities. Tropical
24 deforestation is the largest and most variable single contributor to E_{LUC}.

25 Fire emissions associated with deforestation and tropical peat burning are based on the Global
26 Fire Emissions Database (GFED4; accessed October 2015) described in van der Werf et al. (2010)
27 but with updated burned area (Giglio et al., 2013) as well as burned area from relatively small fires
28 that are detected by satellite as thermal anomalies but not mapped by the burned area approach
29 (Randerson, 2012). The burned area information is used as input data in a modified version of the
30 satellite-driven Carnegie Ames Stanford Approach (CASA) biogeochemical model to estimate
31 carbon emissions associated with fires, keeping track of what fraction of fire emissions was due to

1 deforestation (see van der Werf et al., 2010). The CASA model uses different assumptions to
2 compute decay functions compared to the bookkeeping method, and does not include historical
3 emissions or regrowth from land-use change prior to the availability of satellite data. Comparing
4 coincident CO emissions and their atmospheric fate with satellite-derived CO concentrations
5 allows for some validation of this approach (e.g. van der Werf et al., 2008). Results from the fire-
6 based method to estimate land-use change emissions anomalies added to the bookkeeping mean
7 E_{LUC} estimate are available from 1997 to 2014. Our combination of land-use change CO₂ emissions
8 where the variability of annual CO₂ deforestation emissions is diagnosed from fires assumes that
9 year-to-year variability is dominated by variability in deforestation.

10 **2.2.3 Dynamic Global Vegetation Models (DGVMs)**

11 Land-use change CO₂ emissions have been estimated using an ensemble of ten DGVMs. New
12 model experiments up to year 2014 have been coordinated by the project 'Trends and drivers of
13 the regional-scale sources and sinks of carbon dioxide (TRENDY; Sitch et al., 2015)'. We use only
14 models that have estimated land-use change CO₂ emissions and the terrestrial residual sink
15 following the TRENDY protocol (see Section 2.5.2), thus providing better consistency in the
16 assessment of the causes of carbon fluxes on land. Models use their latest configurations,
17 summarised in Tables 5 and 6.

18 The DGVMs were forced with historical changes in land cover distribution, climate, atmospheric
19 CO₂ concentration, and N deposition. As further described below, each historical DGVM
20 simulation was repeated with a time-invariant pre-industrial land cover distribution, allowing to
21 estimate, by difference with the first simulation, the dynamic evolution of biomass and soil carbon
22 pools in response to prescribed land-cover change. All DGVMs represent deforestation and (to
23 some extent) regrowth, the most important components of E_{LUC} , but they do not represent all
24 processes resulting directly from human activities on land (Table 5). DGVMs represent processes
25 of vegetation growth and mortality, as well as decomposition of dead organic matter associated
26 with natural cycles, and include the vegetation and soil carbon response to increasing atmospheric
27 CO₂ levels and to climate variability and change. In addition, three models explicitly simulate the
28 coupling of C and N cycles and account for atmospheric N deposition (Table 5). The DGVMs are
29 independent from the other budget terms except for their use of atmospheric CO₂ concentration
30 to calculate the fertilization effect of CO₂ on primary production.

1 The DGVMs used a consistent land-use change data set (Hurtt et al., 2011), which provided
2 annual, half-degree, fractional data on cropland, pasture, primary vegetation and secondary
3 vegetation, as well as all underlying transitions between land-use states, including wood harvest
4 and shifting cultivation. This data set used the HYDE (Klein Goldewijk et al., 2011) spatially gridded
5 maps of cropland, pasture, and ice/water fractions of each grid cell as an input. The HYDE data are
6 based on annual FAO statistics of change in agricultural area available to 2012 (FAOSTAT, 2010)
7 For the years 2013 and 2014, the HYDE data were extrapolated by country for pastures and
8 cropland separately based on the trend in agricultural area over the previous 5 years. The HYDE
9 data are independent from the data set used in the bookkeeping method (Houghton, 2003 and
10 updates), which is based primarily on forest area change statistics (FAO, 2010). Although the HYDE
11 land-use change data set indicates whether land-use changes occur on forested or non-forested
12 land, typically only the changes in agricultural areas are used by the models and are implemented
13 differently within each model (e.g. an increased cropland fraction in a grid cell can either be at the
14 expense of grassland, or forest, the latter resulting in deforestation; land cover fractions of the
15 non-agricultural land differ between models). Thus the DGVM forest area and forest area change
16 over time is not consistent with the Forest Resource Assessment of the FAO forest area data used
17 for the bookkeeping model to calculate E_{LUC} . Similarly, model-specific assumptions are applied to
18 convert deforested biomass or deforested area, and other forest product pools, into carbon in
19 some models (Table 5).

20 The DGVM model runs were forced by either 6 hourly CRU-NCEP or by monthly CRU temperature,
21 precipitation, and cloud cover fields (transformed into incoming surface radiation) based on
22 observations and provided on a $0.5^{\circ} \times 0.5^{\circ}$ grid and updated to 2014 (CRU TS3.23; Harris et al.,
23 2015). The forcing data include both gridded observations of climate and global atmospheric CO_2 ,
24 which change over time (Dlugokencky and Tans, 2015), and N deposition (as used in 3 models,
25 Table 5; Lamarque et al., 2010). E_{LUC} is diagnosed in each model by the difference between a
26 model simulation with prescribed historical land cover change and a simulation with constant,
27 preindustrial land cover distribution. Both simulations were driven by changing atmospheric CO_2 ,
28 climate, and in some models N deposition over the period 1860-2014. Using the difference
29 between these two DGVM simulations to diagnose E_{LUC} is not fully consistent with the definition
30 of E_{LUC} in the bookkeeping method (Gasser and Ciais, 2013; Pongratz et al., 2014; Pongratz et al.,
31 2013). The DGVM approach to diagnose land-use change CO_2 emissions would be expected to

1 produce systematically higher E_{LUC} emissions than the bookkeeping approach if all the parameters
2 of the two approaches were the same, which is not the case (see Section 2.5.2).

3 **2.2.4 Other published E_{LUC} methods**

4 Other methods have been used to estimate CO_2 emissions from land-use change. We describe
5 some of the most important methodological differences between the approach used here and
6 other published methods, and for completion, we explain why they are not used in the budget.

7 Different definitions and boundary conditions (e.g. the inclusion of fire management) for E_{LUC} can
8 lead to significantly different estimates within models (Gasser and Ciais, 2013; Hansis et al., 2015;
9 Pongratz et al., 2014) as well as between models and other approaches (Houghton et al., 2012;
10 Smith et al., 2014b). FAO uses the IPCC approach called ‘Tier 1-type’ (e.g. Tubiello et al., 2015) to
11 produce a ‘Land use – forest land’ estimate from the Forest Resources Assessment data updated
12 from the one used in the bookkeeping method described in Section 2.2.1 (MacDicken, 2015). The
13 Tier 1-type method applies a nationally reported mean forest carbon stock change (above and
14 below ground living biomass) to nationally reported net forest area change, across all forest land
15 combined (planted and natural forests). The methods implicitly assume instantaneous loss or gain
16 of mean forest. Thus the IPCC Tier 1-type approach provides an estimate of attributable emissions
17 from the process of land-cover change, but it does not distribute these emissions through time. It
18 also captures some of what the global modelling approach considers residual carbon flux (S_{LAND}), it
19 does not consider loss of soil carbon, and there are no legacy fluxes. Land use fluxes estimated
20 with this method were 0.47 GtC yr^{-1} in 2001-2010 and 0.22 GtC yr^{-1} in 2011-2015 (Federici et al.,
21 2015). This estimate is not directly comparable with E_{LUC} used here because of the different
22 boundary conditions.

23 Recent advances in satellite data leading to higher resolution area change data (e.g. Hansen et al.,
24 2013) and estimates of biomass in live vegetation (e.g. Baccini et al., 2012; Saatchi, 2011), have
25 led to several satellite-based estimates of CO_2 emissions due to tropical deforestation (typically
26 gross loss of forest area; Achard and House, in press). These include estimates of 1.0 GtC yr^{-1} for
27 2000 to 2010 (Baccini et al., 2012), 0.8 GtC yr^{-1} for 2000 to 2005 (Harris, 2012), 0.9 GtC yr^{-1} for
28 2000 to 2010 for net area change (Achard et al., 2014), and 1.3 GtC yr^{-1} 2000 to 2010 (Tyukavina
29 et al., 2015). These estimates include belowground carbon biomass using a scaling factor. Some
30 estimate soil carbon loss, some assume instantaneous emissions, some do not account for

1 regrowth fluxes, and none account for legacy fluxes from land-use change prior to the availability
2 of satellite data. They are mostly estimates of tropical deforestation only, and do not capture
3 regrowth flux after abandonment, or planting (Achard and House, in press). These estimates are
4 also difficult to compare with E_{LUC} used here because they do not fully include legacy fluxes and
5 forest regrowth.

6 **2.2.5 Uncertainty assessment for E_{LUC}**

7 Differences between the bookkeeping, the addition of fire-based interannual variability to the
8 bookkeeping, and DGVM methods originate from three main sources: the land cover change data
9 set, the different approaches used in models, and the different processes represented (Table 5).
10 We examine the results from the ten DGVM models and of the bookkeeping method to assess the
11 uncertainty in E_{LUC} .

12 The uncertainties in annual E_{LUC} estimates are examined using the standard deviation across
13 models, which averages 0.4 GtC yr^{-1} from 1959 to 2014 (Table 7). The mean of the multi-model
14 E_{LUC} estimates is consistent with a combination of the bookkeeping method and fire-based
15 emissions (Le Quéré et al. 2014), with the multi-model mean and bookkeeping method differing
16 by less than 0.5 GtC yr^{-1} over 85% of the time. Based on this comparison, we assess that an
17 uncertainty of $\pm 0.5 \text{ GtC yr}^{-1}$ provides a semi-quantitative measure of uncertainty for annual
18 emissions, and reflects our best value judgment that there is at least 68% chance ($\pm 1\sigma$) that the
19 true land-use change emission lies within the given range, for the range of processes considered
20 here. This is consistent with the uncertainty analysis of Houghton et al. (2012), which partly
21 reflects improvements in data on forest area change using data, and partly more complete
22 understanding and representation of processes in models.

23 The uncertainties in the decadal E_{LUC} estimates are also examined using the DGVM ensemble,
24 although they are likely correlated between decades. The correlations between decades come
25 from (1) common biases in system boundaries (e.g. not counting forest degradation in some
26 models); (2) common definition for the calculation of E_{LUC} from the difference of simulations with
27 and without land-use change (a source of bias vs. the unknown truth); (3) common and uncertain
28 land-cover change input data which also cause a bias, though if a different input data set is used
29 each decade, decadal fluxes from DGVMs may be partly decorrelated; (4) model structural errors
30 (e.g. systematic errors in biomass stocks). In addition, errors arising from uncertain DGVM

1 parameter values would be random but they are not accounted for in this study, since no DGVM
2 provided an ensemble of runs with perturbed parameters.

3 Prior to 1959, the uncertainty in E_{LUC} is taken as $\pm 33\%$, which is the ratio of uncertainty to mean
4 from the 1960s (Table 7), the first decade available. This ratio is consistent with the mean
5 standard deviation of DGMVs land-use change emissions over 1870-1958 (0.38 GtC) over the
6 multi-model mean (1.1 GtC).

7 **2.3 Atmospheric CO₂ growth rate (G_{ATM})**

8 **2.3.1 Global atmospheric CO₂ growth rate estimates**

9 The atmospheric CO₂ growth rate is provided by the US National Oceanic and Atmospheric
10 Administration Earth System Research Laboratory (NOAA/ESRL; Dlugokencky and Tans, 2015),
11 which is updated from Ballantyne et al. (2012). For the 1959-1980 period, the global growth rate is
12 based on measurements of atmospheric CO₂ concentration averaged from the Mauna Loa and
13 South Pole stations, as observed by the CO₂ Program at Scripps Institution of Oceanography
14 (Keeling et al., 1976). For the 1980-2014 time period, the global growth rate is based on the
15 average of multiple stations selected from the marine boundary layer sites with well-mixed
16 background air (Ballantyne et al., 2012), after fitting each station with a smoothed curve as a
17 function of time, and averaging by latitude band (Masarie and Tans, 1995). The annual growth
18 rate is estimated by Dlugokencky and Tans (2015) from atmospheric CO₂ concentration by taking
19 the average of the most recent December-January months corrected for the average seasonal
20 cycle and subtracting this same average one year earlier. The growth rate in units of ppm yr⁻¹ is
21 converted to units of GtC yr⁻¹ by multiplying by a factor of 2.12 GtC per ppm (Ballantyne et al.,
22 2012) for consistency with the other components.

23 The uncertainty around the annual growth rate based on the multiple stations data set ranges
24 between 0.11 and 0.72 GtC yr⁻¹, with a mean of 0.61 GtC yr⁻¹ for 1959-1979 and 0.19 GtC yr⁻¹ for
25 1980-2014, when a larger set of stations were available (Dlugokencky and Tans, 2015). It is based
26 on the number of available stations, and thus takes into account both the measurement errors
27 and data gaps at each station. This uncertainty is larger than the uncertainty of ± 0.1 GtC yr⁻¹
28 reported for decadal mean growth rate by the IPCC because errors in annual growth rate are
29 strongly anti-correlated in consecutive years leading to smaller errors for longer time scales. The
30 decadal change is computed from the difference in concentration ten years apart based on a

1 measurement error of 0.35 ppm. This error is based on offsets between NOAA/ESRL
2 measurements and those of the World Meteorological Organization World Data Center for
3 Greenhouse Gases (NOAA/ESRL, 2015a) for the start and end points (the decadal change
4 uncertainty is the $\sqrt{(2(0.35\text{ppm})^2)(10\text{ yr})^{-1}}$ assuming that each yearly measurement error is
5 independent). This uncertainty is also used in Table 8.

6 The contribution of anthropogenic CO and CH₄ is neglected from the global carbon budget (see
7 Sect. 2.7.1). We assign a high confidence to the annual estimates of G_{ATM} because they are based
8 on direct measurements from multiple and consistent instruments and stations distributed
9 around the world (Ballantyne et al., 2012).

10 In order to estimate the total carbon accumulated in the atmosphere since 1750 or 1870, we use
11 an atmospheric CO₂ concentration of 277 ± 3 ppm or 288 ± 3 ppm, respectively, based on a cubic
12 spline fit to ice core data (Joos and Spahni, 2008). The uncertainty of ±3 ppm (converted to ±1σ) is
13 taken directly from the IPCC's assessment (Ciais et al., 2013). Typical uncertainties in the
14 atmospheric growth rate from ice core data are ±1-1.5 GtC per decade as evaluated from the Law
15 Dome data (Etheridge et al., 1996) for individual 20-year intervals over the period from 1870 to
16 1960 (Bruno and Joos, 1997).

17 **2.4 Ocean CO₂ sink**

18 Estimates of the global ocean CO₂ sink are based on a combination of a mean CO₂ sink estimate
19 for the 1990s from observations, and a trend and variability in the ocean CO₂ sink for 1959-2014
20 from eight global ocean biogeochemistry models. We use two observation-based estimates of
21 S_{OCEAN} available for recent decades to provide a qualitative assessment of confidence in the
22 reported results.

23 **2.4.1 Observation-based estimates**

24 A mean ocean CO₂ sink of 2.2 ± 0.4 GtC yr⁻¹ for the 1990s was estimated by the IPCC (Denman et
25 al., 2007) based on indirect observations and their spread: ocean/land CO₂ sink partitioning from
26 observed atmospheric O₂/N₂ concentration trends (Keeling et al., 2011; Manning and Keeling,
27 2006), an oceanic inversion method constrained by ocean biogeochemistry data (Mikaloff Fletcher
28 et al., 2006), and a method based on penetration time scale for CFCs (McNeil et al., 2003). This is
29 comparable with the sink of 2.0 ± 0.5 GtC yr⁻¹ estimated by Khatiwala et al. (2013) for the 1990s,

1 and with the sink of 1.9 to 2.5 GtC yr⁻¹ estimated from a range of methods for the period 1990-
2 2009 (Wanninkhof et al., 2013), with uncertainties ranging from ±0.3 GtC yr⁻¹ to ±0.7 GtC yr⁻¹. The
3 most direct way for estimating the observation-based ocean sink is from the product of (sea-air
4 pCO₂ difference) x (gas transfer coefficient). Estimates based on sea-air pCO₂ are fully consistent
5 with indirect observations (Zeng et al., 2005), but their uncertainty is larger mainly due to
6 difficulty in capturing complex turbulent processes in the gas transfer coefficient (Sweeney et al.,
7 2007) and because of uncertainties in the pre-industrial river outgas of CO₂ (Jacobson et al., 2007).

8 Both observation-based estimates compute the ocean CO₂ sink and its variability using
9 interpolated measurements of surface ocean fugacity of CO₂ (pCO₂ corrected for the non-ideal
10 behaviour of the gas; Pfeil et al., 2013). The measurements were from the Surface Ocean CO₂
11 Atlas (SOCAT v3; Bakker et al., 2014; Bakker et al., in prep) that contains 14.5 million data to the
12 end of 2014. This was extended with 1.4 million additional measurements over years 2013-2014
13 (see data attribution Table 1A), submitted to SOCAT but not yet fully quality controlled following
14 standard SOCAT procedures. Revisions and corrections to previously reported measurements
15 were also included where they were available. All new data were subjected to an automated
16 quality control system to detect and remove the most obvious errors (e.g. incorrect reporting of
17 metadata such as position, wrong units, clearly unrealistic data etc.). The combined SOCAT v3 and
18 preliminary new 2013-2014 measurements were mapped using a data-driven diagnostic method
19 (Rödenbeck et al., 2013) and a combined self-organising map and feed-forward neural network
20 (Landschützer et al., 2014). The global observation-based estimates were adjusted to remove a
21 background (not part of the anthropogenic ocean flux) ocean source of CO₂ to the atmosphere of
22 0.45 GtC yr⁻¹ from river input to the ocean (Jacobson et al., 2007), to make them comparable to
23 S_{OCEAN} which only represents the annual uptake of anthropogenic CO₂ by the ocean. Several other
24 data-based products are available, **but they show large discrepancies with observed variability
25 that need to be resolved**. Here we used the two data products that had the best fit to
26 observations, distinctly better than most in their representation of tropical and global variability
27 (Rödenbeck et al., 2015).

28 We use the data-based product of Khatiwala et al. (2009) updated by Khatiwala et al. (2013) to
29 estimate the anthropogenic carbon accumulated in the ocean during 1765-1958 (60.2 GtC) and
30 1870-1958 (47.5 GtC), and assume an oceanic uptake of 0.4 GtC for 1750-1765 (for which time no
31 data are available) based on the mean uptake during 1765-1770. The estimate of Khatiwala et al.

1 (2009) is based on regional disequilibrium between surface pCO₂ and atmospheric CO₂, and a
 2 Green's function utilizing transient ocean tracers like CFCs and ¹⁴C to ascribe changes through
 3 time. It does not include changes associated with changes in ocean circulation, temperature and
 4 climate, but these are thought to be small over the time period considered here (Ciais et al.,
 5 2013). The uncertainty in cumulative uptake of ±20 GtC (converted to ±1σ) is taken directly from
 6 the IPCC's review of the literature (Rhein et al., 2013), or about ±30% for the annual values
 7 (Khatiwala et al., 2009).

8 **2.4.2 Global Ocean Biogeochemistry models**

9 The trend in the ocean CO₂ sink for 1959-2014 is computed using a combination of eight global
 10 ocean biogeochemistry models (Table 6). The models represent the physical, chemical and
 11 biological processes that influence the surface ocean concentration of CO₂ and thus the air-sea
 12 CO₂ flux. The models are forced by meteorological reanalysis and atmospheric CO₂ concentration
 13 data available for the entire time period. Models do not include the effects of anthropogenic
 14 changes in nutrient supply. They compute the air-sea flux of CO₂ over grid boxes of 1° to 4° in
 15 latitude and longitude. The ocean CO₂ sink for each model is normalised to the observations, by
 16 dividing the annual model values by their observed average over 1990-1999 and multiplying this
 17 with the observation-based estimate of 2.2 GtC yr⁻¹ (obtained from Keeling et al., 2011; Manning
 18 and Keeling, 2006; McNeil et al., 2003; Mikaloff Fletcher et al., 2006). The ocean CO₂ sink for each
 19 year (*t*) in GtC yr⁻¹ is therefore:

$$S_{OCEAN}(t) = \frac{1}{n} \sum_{m=1}^{m=n} \frac{S_{OCEAN}^m(t)}{S_{OCEAN}^m(1990 - 1999)} \times 2.2 \quad (7)$$

20 where *n* is the number of models. This normalisation ensures that the ocean CO₂ sink for the
 21 global carbon budget is based on observations, whereas the trends and annual values in CO₂ sinks
 22 are from model estimates. The normalisation based on a ratio assumes that if models over or
 23 underestimate the sink in the 1990s, it is primarily due to the process of diffusion, which depends
 24 on the gradient of CO₂. Thus a ratio is more appropriate than an offset as it takes into account the
 25 time-dependence of CO₂ gradients in the ocean. The mean uncorrected ocean CO₂ sink from the
 26 eight models for 1990-1999 ranges between 1.6 and 2.4 GtC yr⁻¹, with a multi model mean of 1.9
 27 GtC yr⁻¹.

1 **2.4.3 Uncertainty assessment for S_{OCEAN}**

2 The uncertainty around the mean ocean sink of anthropogenic CO_2 was quantified by Denman et
3 al. (2007) for the 1990s (see Section 2.4.1). To quantify the uncertainty around annual values, we
4 examine the standard deviation of the normalised model ensemble. We use further information
5 from the two data-based products to assess the confidence level. The average standard deviation
6 of the normalised ocean model ensemble is 0.13 GtC yr^{-1} during 1980-2010 (with a maximum of
7 0.27), but it increases as the model ensemble goes back in time, with a standard deviation of 0.22
8 GtC yr^{-1} across models in the 1960s. We estimate that the uncertainty in the annual ocean CO_2
9 sink is about $\pm 0.5 \text{ GtC yr}^{-1}$ from the fractional uncertainty of the data uncertainty of $\pm 0.4 \text{ GtC yr}^{-1}$
10 and standard deviation across models of up to $\pm 0.27 \text{ GtC yr}^{-1}$, reflecting both the uncertainty in
11 the mean sink from observations during the 1990's (Denman et al., 2007; Section 2.4.1) and in the
12 interannual variability as assessed by models.

13 We examine the consistency between the variability of the model-based and the data-based
14 products to assess confidence in S_{OCEAN} . The interannual variability of the ocean fluxes (quantified
15 as the standard deviation) of the two data-based estimates for 1986-2014 (where they overlap) is
16 $\pm 0.38 \text{ GtC yr}^{-1}$ (Rödenbeck et al., 2014) and $\pm 0.40 \text{ GtC yr}^{-1}$ (Landschützer et al., 2015), compared
17 to $\pm 0.27 \text{ GtC yr}^{-1}$ for the normalised model ensemble. The standard deviation includes a
18 component of trend and decadal variability in addition to interannual variability, and their relative
19 influence differs across estimates. The phase is generally consistent between estimates, with a
20 higher ocean CO_2 sink during El Niño events. The annual data-based estimates correlate with the
21 ocean CO_2 sink estimated here with a correlation of $r = 0.51$ (0.34 to 0.58 for individual models),
22 and $r = 0.71$ (0.54 to 0.72) for the data-based estimates of Rödenbeck et al. (2014) and
23 Landschützer et al. (2015), respectively (simple linear regression), but their mutual correlation is
24 only 0.55 . The use of annual data for the correlation may reduce the strength of the relationship
25 because the dominant source of variability associated with El Niño events is less than one year.
26 We assess a medium confidence level to the annual ocean CO_2 sink and its uncertainty because
27 they are based on multiple lines of evidence, and the results are consistent in that the interannual
28 variability in the model and data-based estimates are all generally small compared to the
29 variability in atmospheric CO_2 growth rate. Nevertheless the various results do not show
30 agreement in interannual variability on the global scale or for the relative roles of the annual and
31 decadal variability compared to the trend.

1 **2.5 Terrestrial CO₂ sink**

2 The difference between, on the one hand fossil fuel (E_{FF}) and land-use change emissions (E_{LUC}),
 3 and on the other hand the growth rate in atmospheric CO₂ concentration (G_{ATM}) and the ocean
 4 CO₂ sink (S_{OCEAN}), is attributable to the net sink of CO₂ in terrestrial vegetation and soils (S_{LAND}),
 5 within the given uncertainties (Eq. 1). Thus, this sink can be estimated as the residual of the other
 6 terms in the mass balance budget, as well as directly calculated using DGVMs. The residual land
 7 sink (S_{LAND}) is thought to be in part because of the fertilising effect of rising atmospheric CO₂ on
 8 plant growth, N deposition and effects of climate change such as the lengthening of the growing
 9 season in northern temperate and boreal areas. S_{LAND} does not include gross land sinks directly
 10 resulting from land-use change (e.g. regrowth of vegetation) as these are estimated as part of the
 11 net land use flux (E_{LUC}). System boundaries make it difficult to attribute exactly CO₂ fluxes on land
 12 between S_{LAND} and E_{LUC} (Erb et al., 2013), and by design most of the uncertainties in our method
 13 are allocated to S_{LAND} for those processes that are poorly known or represented in models.

14 **2.5.1 Residual of the budget**

15 For 1959-2014, the terrestrial carbon sink was estimated from the residual of the other budget
 16 terms by rearranging Eq. (1):

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

17 The uncertainty in S_{LAND} is estimated annually from the root sum of squares of the uncertainty in
 18 the right-hand terms assuming the errors are not correlated. The uncertainty averages to ± 0.8
 19 GtC yr⁻¹ over 1959-2014 (Table 7). S_{LAND} estimated from the residual of the budget includes, by
 20 definition, all the missing processes and potential biases in the other components of Eq. (8).

21 **2.5.2 DGVMs**

22 A comparison of the residual calculation of S_{LAND} in Eq. (8) with estimates from DGVMs as used to
 23 estimate E_{LUC} in Sect. 2.2.3, but here excluding the effects of changes in land cover (using a
 24 constant pre-industrial land cover distribution), provides an independent estimate of the
 25 consistency of S_{LAND} with our understanding of the functioning of the terrestrial vegetation in
 26 response to CO₂ and climate variability (Table 7). As described in Sect. 2.2.3, the DGVM runs that
 27 exclude the effects of changes in land cover include all climate variability and CO₂ effects over
 28 land, but do not include reductions in CO₂ sink capacity associated with human activity directly

1 affecting changes in vegetation cover and management, which by design is allocated to E_{LUC} . This
2 effect has been estimated to have led to a reduction in the terrestrial sink by 0.5 GtC yr^{-1} since
3 1750 (Gitz and Ciais, 2003). The models in this configuration estimate the mean and variability of
4 S_{LAND} based on atmospheric CO_2 and climate, and thus both terms can be compared to the budget
5 residual. We apply three criteria for minimum model realism by including only those models
6 with (1) steady state after spin up, (2) net land fluxes ($S_{LAND} - E_{LUC}$) that is a carbon sink over the
7 1990s as constrained by global atmospheric and oceanic observations (McNeill et al 2003,
8 Manning and Keeling 2006, Mikaloff-Fletcher et al., 2006), and (3) global E_{LUC} that is a carbon
9 source over the 1990s. Ten models met these three criteria.

10 The annual standard deviation of the CO_2 sink across the ten DGVMs averages to $\pm 0.7 \text{ GtC yr}^{-1}$ for
11 the period 1959 to 2014. The model mean, over different decades, correlates with the budget
12 residual with $r = 0.71$ (0.52 to $r = 0.71$ for individual models). The standard deviation is similar to
13 that of the five model ensembles presented in Le Quéré et al. (2009), but the correlation is
14 improved compared to $r = 0.54$ obtained in the earlier study. The DGVM results suggest that the
15 sum of our knowledge on annual CO_2 emissions and their partitioning is plausible (see Discussion),
16 and provide insight on the underlying processes and regional breakdown. However as the
17 standard deviation across the DGVMs (e.g. $\pm 0.9 \text{ GtC yr}^{-1}$ for year 2014) is of the same magnitude
18 as the combined uncertainty due to the other components (E_{FF} , E_{LUC} , G_{ATM} , S_{OCEAN} ; Table 7), the
19 DGVMs do not provide further reduction of uncertainty on the annual terrestrial CO_2 sink
20 compared to the residual of the budget (Eq. 8). Yet, DGVM results are largely independent from
21 the residual of the budget, and it is worth noting that the residual method and ensemble mean
22 DGVM results are consistent within their respective uncertainties. We attach a medium
23 confidence level to the annual land CO_2 sink and its uncertainty because the estimates from the
24 residual budget and averaged DGVMs match well within their respective uncertainties, and the
25 estimates based on the residual budget are primarily dependent on E_{FF} and G_{ATM} , both of which
26 are well constrained.

27 **2.6 The atmospheric perspective**

28 The world-wide network of atmospheric measurements can be used with atmospheric inversion
29 methods to constrain the location of the combined total surface CO_2 fluxes from all sources,
30 including fossil and land-use change emissions and land and ocean CO_2 fluxes. The inversions
31 assume E_{FF} to be well known, and they solve for the spatial and temporal distribution of land and

1 ocean fluxes from the residual gradients of CO₂ between stations that are not explained by
2 emissions. Inversions used atmospheric CO₂ data to the end of 2014 (including preliminary values
3 in some cases), and three atmospheric CO₂ inversions (Table 6) to infer the total CO₂ flux over land
4 regions, and the distribution of the total land and ocean CO₂ fluxes for the mid-high latitude
5 northern hemisphere (30°N-90°N), Tropics (30°S-30°N) and mid-high latitude region of the
6 southern hemisphere (30°S-90°S). We focus here on the largest and most consistent sources of
7 information, and use these estimates to comment on the consistency across various data streams
8 and process-based estimates.

9 **2.6.1 Atmospheric inversions**

10 The three inversion systems used in this release are the CarbonTracker (Peters et al., 2010), the
11 Jena CarboScope (Rödenbeck, 2005), and MACC (Chevallier et al., 2005). They are based on the
12 same Bayesian inversion principles that interpret the same, for the most part, observed time
13 series (or subsets thereof), but use different methodologies that represent some of the many
14 approaches used in the field. This mainly concerns the time resolution of the estimates (i.e.
15 weekly or monthly), spatial breakdown (i.e. grid size), assumed correlation structures, and
16 mathematical approach. The details of these approaches are documented extensively in the
17 references provided. Each system uses a different transport model, which was demonstrated to
18 be a driving factor behind differences in atmospheric-based flux estimates, and specifically their
19 global distribution (Stephens et al., 2007).

20 The three inversions use atmospheric CO₂ observations from various flask and in situ networks.
21 They prescribe spatial and global E_{FF} that can vary from that presented here. The CarbonTracker
22 and MACC inversions prescribed the same global E_{FF} than in section 2.1.1, during 2010-2014 for
23 CarbonTracker, and during 1979-2014 in MACC. The Jena-s81_v3.7 inversion uses E_{FF} from
24 EDGAR4.2. Different spatial and temporal distributions of E_{FF} were prescribed in each inversion.

25 Given their prescribed map of E_{FF}, each inversion estimates natural fluxes from a similar set of
26 surface CO₂ measurement stations, and CarbonTracker additionally uses two sites of aircraft CO₂
27 vertical profiles over the Amazon and Siberia, regions where surface observations are sparse. The
28 atmospheric transport models of each inversion are TM5 for CarbonTracker, TM3 for Jena-
29 s81_v3.7, and LMDZ for MACC. These three models are based on the same ECMWF wind fields.
30 The three inversions use different prior natural fluxes, which partly influences their optimized

1 fluxes. MACC assumes that the prior land flux is zero on the annual mean in each grid cell of the
2 transport model, so that any sink or source on land is entirely reflecting the information brought
3 by atmospheric measurements. CarbonTracker simulates a small prior sink on land from the
4 SIBCASA model that results from regrowth following fire disturbances of an otherwise net zero
5 biosphere. Jena-s81_v3.7 assumes a prior sink on land as well from the LPJ model. Inversion
6 results for the sum of natural ocean and land fluxes (Fig. 8) are better constrained in the Northern
7 hemisphere (NH) than in the Tropics, because of the higher measurement stations density in the
8 NH.

9 Finally, results from atmospheric inversions include the natural CO₂ fluxes from rivers (which need
10 to be taken into account to allow comparison to other sources), and chemical oxidation of
11 reactive carbon-containing gases (which are neglected here). These inverse estimates are not truly
12 independent of the other estimates presented here as the atmospheric observations include a set
13 of observations used to estimate the global atmospheric growth rate (Section 2.3). However they
14 provide new information on the regional distribution of fluxes.

15 We focus the analysis on two known strengths of the inverse approach: the derivation of the year-
16 to-year changes in total land fluxes ($E_{LUC} + S_{LAND}$) consistent with the whole network of
17 atmospheric observations, and the spatial breakdown of land and ocean fluxes ($E_{LUC} + S_{LAND} +$
18 S_{OCEAN}) across large regions of the globe. The total land flux correlates well with those estimated
19 from the budget residual (Eq. 1) with correlations for the annual time series ranging from $r = 0.89$
20 to 0.93, and with the DGVM multi-model mean with correlations for the annual time series
21 ranging from $r = 0.71$ to 0.80 ($r = 0.49$ to 0.81 for individual DGVMs and inversions). The spatial
22 breakdown is discussed in Section 3.1.3.

23 **2.7 Processes not included in the global carbon budget**

24 **2.7.1 Contribution of anthropogenic CO and CH₄ to the global carbon budget**

25 Anthropogenic emissions of CO and CH₄ to the atmosphere are eventually oxidized to CO₂ and
26 thus are part of the global carbon budget. These contributions are omitted in Eq. (1), but an
27 attempt is made in this section to estimate their magnitude, and identify the sources of
28 uncertainty. Anthropogenic CO emissions are from incomplete fossil fuel and biofuel burning and
29 deforestation fires. The main anthropogenic emissions of fossil CH₄ that matter for the global

1 carbon budget are the fugitive emissions of coal, oil and gas upstream sectors (see below). These
2 emissions of CO and CH₄ contribute a net addition of fossil carbon to the atmosphere.

3 In our estimate of E_{FF} we assumed (Section 2.1.1) that all the fuel burned is emitted as CO₂, thus
4 CO anthropogenic emissions and their atmospheric oxidation into CO₂ within a few months are
5 already counted implicitly in E_{FF} and should not be counted twice (same for E_{LUC} and
6 anthropogenic CO emissions by deforestation fires). Anthropogenic emissions of fossil CH₄ are not
7 included in E_{FF}, because these fugitive emissions are not included in the fuel inventories. Yet they
8 contribute to the annual CO₂ growth rate after CH₄ gets oxidized into CO₂. Anthropogenic
9 emissions of fossil CH₄ represent 15% of total CH₄ emissions (Kirschke et al., 2013) that is 0.061
10 GtC yr⁻¹ for the past decade. Assuming steady state, these emissions are all converted to CO₂ by
11 OH oxidation, and thus explain 0.06 GtC yr⁻¹ of the global CO₂ growth rate in the past decade.
12 Other anthropogenic changes in the sources of CO and CH₄ from wildfires, biomass, wetlands,
13 ruminants or permafrost changes are similarly assumed to have a small effect on the CO₂ growth
14 rate.

15 **2.7.2 Anthropogenic carbon fluxes in the land to ocean aquatic continuum**

16 The approach used to determine the global carbon budget considers only anthropogenic CO₂
17 emissions and their partitioning among the atmosphere, ocean and land. In this analysis, the land
18 and ocean reservoirs that take up anthropogenic CO₂ from the atmosphere are conceived as
19 independent carbon storage repositories. This approach thus omits that carbon is continuously
20 displaced along the land-ocean aquatic continuum (LOAC) comprising freshwaters, estuaries and
21 coastal areas (Bauer et al., 2013; Regnier et al., 2013). A significant fraction of this lateral carbon
22 flux is entirely 'natural' and is thus a steady state component of the pre-industrial carbon cycle.
23 The remaining fraction is anthropogenic carbon entrained into the lateral transport loop of the
24 LOAC, a perturbation that is relevant for the global carbon budget presented here.

25 The results of the analysis of Regnier et al. (2013) can be summarized in three points of relevance
26 to the anthropogenic CO₂ budget. First, the anthropogenic carbon input from land to
27 hydrosphere, F_{LH}, estimated at 1 ± 0.5 GtC yr⁻¹ is significant compared to the other terms of Eq. (1)
28 (Table 8), and implies that only a portion of the anthropogenic CO₂ taken up by land ecosystems
29 remains sequestered in soil and biomass pools. Second, some of the exported anthropogenic
30 carbon is stored in the LOAC (ΔC_{LOAC} , 0.55 ± 0.3 GtC yr⁻¹) and some is released back to the

1 atmosphere as CO₂ (E_{LOAC} , 0.35 ± 0.2 GtC yr⁻¹), the magnitude of these fluxes resulting from the
 2 combined effects of freshwaters, estuaries and coastal seas. Third, a small fraction of
 3 anthropogenic carbon displaced by the LOAC is transferred to the open ocean where it
 4 accumulates (F_{HO} , $0.1 \pm > 0.05$ GtC yr⁻¹). The anthropogenic perturbation of the carbon fluxes from
 5 land to ocean does not contradict the method used in Section 2.5 to define the ocean sink and
 6 residual terrestrial sink. However, it does point to the need to account for the fate of
 7 anthropogenic carbon once it is removed from the atmosphere by land ecosystems (summarized
 8 in Fig 2). In theory, direct estimates of changes of the ocean inorganic carbon inventory over time
 9 would see the land flux of anthropogenic carbon and would thus have a bias relative to air-sea flux
 10 estimates and tracer based reconstructions. However, currently the value is small enough to be
 11 not noticeable relative to the errors in the individual techniques.

12 The residual terrestrial sink in a budget that accounts for the LOAC will be larger than S_{LAND} , as the
 13 flux is partially offset by the net source of CO₂ to the atmosphere, i.e. E_{LOAC} , of 0.35 ± 0.3 GtC yr⁻¹
 14 from rivers, estuaries and coastal seas:

$$S_{LAND+LOAC} = E_{FF} + E_{LUC} - (G_{ATM} + S_{OCEAN}) + E_{LOAC} \quad (9)$$

15 The residual terrestrial sink (S_{LAND}) is 3.0 ± 0.8 GtC yr⁻¹ for 2005-2014 as calculated according to Eq.
 16 (8; Table 7) while $S_{LAND+LOAC}$ is 3.3 ± 0.9 GtC yr⁻¹ over the same time period. A fraction of
 17 anthropogenic CO₂ taken up by land ecosystems is exported to the LOAC (F_{LH}). With the LOAC
 18 included, we now have:

$$\Delta C_{TE} = S_{LAND+LOAC} - E_{LUC} - F_{LH} \quad (10)$$

19 where ΔC_{TE} is the change in annual terrestrial ecosystems carbon storage, including land
 20 vegetation, litter and soil, ΔC_{TE} is 1.4 GtC yr⁻¹ for the period 2005-2014. It is notably smaller than
 21 what would be calculated in a traditional budget that ignores the LOAC. In this case, the change in
 22 carbon storage is estimated as 2.1 Gt C yr⁻¹ from the difference between S_{LAND} (3.0 Gt C yr⁻¹) and
 23 E_{LUC} (0.9 Gt C yr⁻¹; Table 8). All estimates of LOAC are given with low confidence, because they
 24 originate from a single source. The carbon budget presented here implicitly incorporates the
 25 fluxes from the LOAC with S_{LAND} . We do not attempt to separate these fluxes because the
 26 uncertainties in either estimate are too large, and there is insufficient information available to
 27 estimate the LOAC fluxes on an annual basis.

1 **3 Results**

2 **3.1 Global carbon budget averaged over decades and its variability**

3 The global carbon budget averaged over the last decade (2005-2014) is shown in Fig. 2. For this
4 time period, 91% of the total emissions ($E_{FF} + E_{LUC}$) were caused by fossil fuels and industry, and
5 9% by land-use change. The total emissions were partitioned among the atmosphere (44%), ocean
6 (26%) and land (30%). All components except land-use change emissions have grown since 1959
7 (Figs. 3 and 4), with important interannual variability in the atmospheric growth rate and in the
8 land CO_2 sink (Fig. 4), and some decadal variability in all terms (Table 8).

9 **3.1.1 CO_2 emissions**

10 Global CO_2 emissions from fossil fuels and industry have increased every decade from an average
11 of $3.1 \pm 0.2 \text{ GtC yr}^{-1}$ in the 1960s to an average of $9.0 \pm 0.5 \text{ GtC yr}^{-1}$ during 2005-2014 (Table 8 and
12 Fig. 5). The growth rate in these emissions decreased between the 1960s and the 1990s, from
13 $4.5\% \text{ yr}^{-1}$ in the 1960s (1960-1969), $2.9\% \text{ yr}^{-1}$ in the 1970s (1970-1979), $1.9\% \text{ yr}^{-1}$ in the 1980s
14 (1980-1989), and finally to $1.0\% \text{ yr}^{-1}$ in the 1990s (1990-1999), before it began increasing again in
15 the 2000s at an average growth rate of $3.2\% \text{ yr}^{-1}$, decreasing to $2.2\% \text{ yr}^{-1}$ for the last decade
16 (2005-2014). In contrast, CO_2 emissions from land-use change have remained constant, in our
17 analysis at around $1.5 \pm 0.5 \text{ GtC yr}^{-1}$ between 1960-1999 and $1.0 \pm 0.5 \text{ GtC yr}^{-1}$ during 2000-2014.
18 The decrease in emissions from land-use change between the 1990s and 2000s is highly uncertain.
19 It is not found in the current ensemble of the DGVMs (Fig. 6), which are otherwise consistent with
20 the bookkeeping method within their respective uncertainty (Table 7). It is also not found in the
21 study of tropical deforestation of Achard et al. (2014) where the fluxes in the 1990s were similar
22 to those of the 2000s and outside our uncertainty range. A new study based on FAO data to 2015
23 (Federici et al., 2015) suggests that E_{LUC} decreased during 2011-2015 compared to 2001-2010.

24 **3.1.2 Partitioning**

25 The growth rate in atmospheric CO_2 increased from $1.7 \pm 0.1 \text{ GtC yr}^{-1}$ in the 1960s to $4.4 \pm 0.1 \text{ GtC}$
26 yr^{-1} during 2005-2014 with important decadal variations (Table 8). Both ocean and land CO_2 sinks
27 increased roughly in line with the atmospheric increase, but with significant decadal variability on
28 land (Table 8). The ocean CO_2 sink increased from $1.1 \pm 0.5 \text{ GtC yr}^{-1}$ in the 1960s to $2.6 \pm 0.5 \text{ GtC}$
29 yr^{-1} during 2005-2014, with interannual variations of the order of a few tenths of GtC yr^{-1} generally
30 showing an increased ocean sink during El Niño (i.e. 1982-1983, 1991-1993, 1997-1998) events

1 (Fig. 7; Rödenbeck et al., 2014). Although there is some coherence between the ocean models and
2 data products and among data products, their mutual correlation is weak and highlights
3 disagreement on the exact amplitude of the interannual variability, and on the relative
4 importance of the trend versus the variability (Section 2.4.3 and Fig. 7). As shown in Fig. 7, the two
5 data products and most model estimates produce a mean CO₂ sink for the 1990s that is below the
6 mean assessed by the IPCC from indirect (but arguably more reliable) observations (Denman et al.,
7 2007; Section 2.4.1). This discrepancy suggests we may need to reassess estimates of the mean
8 ocean carbon sinks.

9 The land CO₂ sink increased from 1.7 ± 0.7 GtC yr⁻¹ in the 1960s to 3.0 ± 0.8 GtC yr⁻¹ during 2005-
10 2014, with important interannual variations of up to 2 GtC yr⁻¹ generally showing a decreased land
11 sink during El Niño events, overcompensating the increase in ocean sink and accounting for the
12 enhanced atmospheric growth rate during El Niño events. The high uptake anomaly around year
13 1991 is thought to be caused by the effect of the volcanic eruption of Mount Pinatubo on climate
14 and is not generally reproduced by the DGVMs, but it is assigned to the land by the two inverse
15 systems that include this period (Fig. 6). The larger land CO₂ sink during 2005-2014 compared to
16 the 1960s is reproduced by all the DGVMs in response to combined atmospheric CO₂ increase,
17 climate and variability (3.0 ± 0.5 GtC yr⁻¹ for the period 2005-2014 and average change of 1.9 GtC
18 yr⁻¹ relative to the 1960s), consistent with the budget residual and reflecting a common
19 knowledge of the processes (Table 7). The DGVM ensemble mean of 3.0 ± 0.5 GtC yr⁻¹ also
20 reproduces the observed mean for the period 2005-2014 calculated from the budget residual
21 (Table 7).

22 The total CO₂ fluxes on land ($E_{LUC} + S_{LAND}$) constrained by the atmospheric inversions show in
23 general very good agreement with the global budget estimate, as expected given the strong
24 constrains of G_{ATM} and the small relative uncertainty typically assumed on S_{OCEAN} and E_{FF} by
25 inversions. The total land flux is of similar magnitude for the decadal average, with estimates for
26 2005-2014 from the three inversions of 2.0, 2.0 and 3.3 GtC yr⁻¹ compared to 2.1 ± 0.7 GtC yr⁻¹ for
27 the total flux computed with the carbon budget from other terms in Eq. 1 (Table 7). The three
28 inversions' total land sink would be 1.6, 1.6 and 2.9 GtC yr⁻¹ when including a mean river flux
29 adjustment of 0.45 GtC yr⁻¹, though the exact adjustment would be smaller when taking into
30 account the anthropogenic contribution to river fluxes (Section 2.7.2). The interannual variability
31 of the inversions also matched the residual-based S_{LAND} closely (Fig. 6). The total land flux from the

1 DGVM multi-model mean also compares well with the estimate from the carbon budget and
2 atmospheric inversions, with a decadal mean of $1.6 \pm 0.4 \text{ GtC yr}^{-1}$ (Table 7; 2005-2014), although
3 individual models differ by several GtC for some years (Fig. 6).

4 **3.1.3 Distribution**

5 Fig 8 shows the partitioning of the total surface fluxes excluding emissions from fossil fuels and
6 industry ($S_{\text{LAND}} + S_{\text{OCEAN}} + E_{\text{LUC}}$) according to the process models in the ocean and on land, and to
7 the three atmospheric inversions. The total surface fluxes provide information on the regional
8 distribution of those fluxes by latitude band (Fig. 8). The global mean CO_2 fluxes from process
9 models for 2005-2014 is $4.2 \pm 0.5 \text{ GtC yr}^{-1}$. This is comparable to the fluxes of $4.7 \pm 0.5 \text{ GtC yr}^{-1}$
10 inferred from the remainder of the carbon budget ($E_{\text{FF}} - G_{\text{ATM}}$ in Equation 1; Table 8) within their
11 respective uncertainties. The total CO_2 fluxes from the three inversions range between 4.4 and 4.9
12 GtC yr^{-1} , consistent with the carbon budget as expected from the constraints on the inversions.

13 In the South (south of 30°S), the atmospheric inversions and process models all suggest a CO_2 sink
14 for 2005-2014 of between 1.2 and 1.5 GtC yr^{-1} (Fig. 8), although the details of the interannual
15 variability are not fully consistent across methods. The interannual variability in the South is low
16 because of the dominance of ocean area with low variability compared to land areas.

17 In the Tropics (30°S - 30°N), both the atmospheric inversions and process models suggest the
18 carbon balance in this region is close to neutral over the past decade, with fluxes for 2005-2014
19 ranging between -0.6 and $+0.6 \text{ GtC yr}^{-1}$. The three inversions consistently allocate more year-to-
20 year variability of CO_2 fluxes to the Tropics compared to the North (north of 30°N ; Fig. 8). This
21 variability is dominated by land fluxes. Inversions are consistent with each other and with the
22 mean of process models.

23 In the North (north of 30°N), the inversions and process models are not in full agreement on the
24 magnitude of the CO_2 sink with the ensemble mean of the process models suggesting a total
25 northern hemisphere sink for 2005-2014 of $2.3 \pm 0.4 \text{ GtC yr}^{-1}$ while the three inversions estimate a
26 sink of 2.5, 3.4 and 3.6 GtC yr^{-1} . The mean difference can only partly be explained by the influence
27 of river fluxes, as this flux in the Northern Hemisphere would be less than 0.45 GtC yr^{-1} ,
28 particularly when the anthropogenic contribution to river fluxes are accounted for. The
29 CarbonTracker inversion is within one standard deviation of the process models for the mean sink

1 during their overlap period. MACC and Jena-s81_v3.7 give a higher sink in the North than the
2 process models, and a correspondingly higher source in the Tropics. Differences between
3 CarbonTracker and MACC, Jena-s81_v3.7 may be related to differences in inter-hemispheric
4 mixing time of their transport models, and other inversion settings. Differences between the
5 mean fluxes of MACC, Jena-s81_v3.7 and the ensemble of process models cannot be simply
6 explained. They could either reflect a bias in these two inversions, or missing processes or biases
7 in the process models, such as the lack of adequate parameterizations for forest management in
8 the North and for forest degradation emissions in Tropics for the DGVMs.

9 The estimated contribution of the North from process models is sensitive both to the ensemble of
10 process models used and to the specifics of each inversion. Indeed the process model results from
11 Le Quéré et al. (2015) included a slightly different model ensemble (see Table 6) with no
12 assessment of minimum model realism. It showed a larger model spread and smaller sink ($2.0 \pm$
13 0.8 GtC yr^{-1} for the latest decade), with also different trend in the 1960s. All three inversions show
14 substantial differences in variability and/or trend, and one inversion substantial difference in the
15 mean Northern sink.

16 **3.2 Global carbon budget for year 2014 and emissions projection for 2015**

17 **3.2.1 CO₂ emissions**

18 Global CO₂ emissions from fossil fuels and industry reached $9.8 \pm 0.5 \text{ GtC}$ in 2014 (Fig. 5),
19 distributed among coal (42%), oil (33%), gas (19%), cement (5.7%) and gas flaring (0.6%). The first
20 four categories increased by 0.4%, 0.8%, 0.4% and 2.5% respectively over the previous year. Due
21 to lack of data, gas flaring in 2012-2014 are assumed the same as 2011.

22 Emissions in 2014 were 0.6% higher than in 2013, an increase well below the decadal average of
23 $2.2\% \text{ yr}^{-1}$ (2005-2014). Growth in 2014 is lower than our projection of $2.5\% \text{ yr}^{-1}$ made last year (Le
24 Quéré et al., 2015) based on an estimated GDP growth of $3.3\% \text{ yr}^{-1}$ and a decrease in I_{FF} of -0.7%
25 yr^{-1} (Table 9), and also outside the provided likely range of 1.3-3.5%. The latest estimate of GDP
26 growth for 2014 was still $3.3\% \text{ yr}^{-1}$ (IMF, 2015) and hence I_{FF} improved by $2.7\% \text{ yr}^{-1}$. This I_{FF} is low
27 compared to recent years (Table 9), but not outside the range of variability observed in recent
28 decades, suggesting that our uncertainty range may have been underestimated. Almost half of the
29 lower growth compared to expectations can be attributed to a lower growth in emissions than
30 anticipated in China (1.1% compared to 4.5% in our projection; Friedlingstein et al. 2014), which

1 primarily reflects structural changes in China's economy (Green and Stern, 2015). Similar
2 structural change occurred following the Global Financial Crisis of 2008-2009 that particularly
3 affected western economies, which also made the emissions projections based on GDP
4 temporarily problematic and outside of the steady behaviour assumed by the GDP/intensity
5 approach (Peters et al. 2012). For this reason we provide an emissions projection with explicit
6 projection for China based on energy and cement data during January – August 2015 (see Section
7 2.1.4). Climatic variability could also have contributed to the lower emissions in China (from
8 reported high rainfall possibly leading to higher hydropower capacity utilisation), and in Europe
9 and the USA where the combined emissions changes account for 37% of the lower growth
10 compared to expectations (Friedlingstein et al. 2014).

11 Using separate projections for China, the USA, and the rest of the world as described in Section
12 2.1.4, we project that the growth in global CO₂ emissions from fossil fuels and cement production
13 will be near or slightly below zero in 2015, with a change of -0.6% (range of -1.6% to +0.5%) from
14 2014 levels. Our method is imprecise and contains several assumptions that could influence the
15 results beyond the given range, and as such is indicative only. Within the given assumptions,
16 global emissions decrease to 9.7 ± 0.5 GtC (35.7 ± 1.8 GtCO₂) in 2015, but are still 59% above
17 emissions in 1990.

18 For China, the expected change based largely on available data during January to August (see
19 Section 2.1.4) is for a decrease in emissions of -3.9% (range of -4.6% to -1.1%) in 2015 compared
20 to 2014. This uncertainty includes a range of -4.6% to -3.2% considering different adjustments for
21 stocks and no changes in the carbon content of coal, and is based on estimated decreases in
22 apparent coal consumption (-5.3%) and cement production (-5.0%) and estimated growth in
23 apparent oil (+3.2%) and natural gas (+1.4%) consumption. However, there are additional
24 uncertainties from the carbon content of coal. While China's Energy Statistical Yearbooks indicate
25 declining carbon content over recent years, preliminary data suggest an increase of up to 3% in
26 2014. The Chinese government has introduced measures expressly to address the declining
27 quality of coal (which also leads to lower carbon content) by closing lower-quality mines and
28 placing restrictions on the quality of imported coal. Allowing for a similar increase in 2015 (0% to
29 3%), we expand the uncertainty range of China's emissions growth to -4.6% to -1.1%. Finally,
30 China revised their emissions statistics upwards recently, which would affect the absolute value of
31 emissions for China (but not the trend). With a slightly higher global contribution for China, our

1 projection of global emissions “growth” for 2015 would decline further from -0.6% to -0.8% , a
2 small difference that falls within our uncertainty range.

3 For the USA, the EIA emissions projection for 2015 combined with cement data from USGS gives a
4 decrease of -1.5% (range of -5.5% to $+0.3\%$) compared to 2014. For the rest of the world, the
5 expected growth for 2015 of $+1.2\%$ (range of -0.2% to $+2.6\%$) is computed using the GDP projection
6 for the world excluding China and the USA of 2.3% made by the IMF (2015) and a decrease in I_{FF} of
7 $-1.1\% \text{ yr}^{-1}$ which is the average from 2005-2014. The uncertainty range is based on the standard
8 deviation of the interannual variability in I_{FF} during 2005-2014 of $\pm 1.4\%$.

9 In 2014, the largest contributions to global CO_2 emissions were from China (27%; Liu et al., 2015),
10 the USA (15%), the EU (28 member states; 10%), and India (7%), with the percentages compared
11 to the global total including bunker fuels (3.0%). These four regions account for 59% of global
12 emissions. Growth rates for these countries from 2013 to 2014 were 1.2% (China), 0.8% (USA),
13 -5.8% (EU28), and 8.6% (India). The per-capita CO_2 emissions in 2014 were $1.3 \text{ tC person}^{-1} \text{ yr}^{-1}$ for
14 the globe, and were 4.8 (USA), 1.9 (China), 1.8 (EU28) and 0.5 (India) $\text{tC person}^{-1} \text{ yr}^{-1}$ for the four
15 highest emitting countries (Fig. 5e).

16 Territorial emissions in Annex B countries have decreased slightly by 0.1% per year on average
17 from 1990-2013, while consumption emissions grew at $0.4\% \text{ yr}^{-1}$ (Fig. 5c). In non-Annex B
18 countries, territorial emissions have grown at $4.4\% \text{ yr}^{-1}$, while consumption emissions have grown
19 at $4.1\% \text{ yr}^{-1}$. In 1990, 66% of global territorial emissions were emitted in Annex B countries (34% in
20 non-Annex B, and 2% in bunker fuels used for international shipping and aviation), while in 2013
21 this had reduced to 38% (58% in non-Annex B, and 3% in bunker fuels). In terms of consumption
22 emissions this split was 64% in 1990 and 39% in 2013 (34% to 55% in non-Annex B). The difference
23 between territorial and consumption emissions (the net emission transfer via international trade)
24 from non-Annex B to Annex B countries has increased from near zero in 1990 to 0.3 GtC yr^{-1}
25 around 2005 and remained relatively stable between 2006 and 2013 (Fig. 5). The increase in net
26 emission transfers of 0.30 GtC yr^{-1} between 1990 and 2013 compares with the emission reduction
27 of 0.37 GtC yr^{-1} in Annex B countries. These results show the importance of net emission transfer
28 via international trade from non-Annex B to Annex B countries, and the stabilisation of emissions
29 transfer when averaged over Annex B countries during the past decade. In 2013, the biggest
30 emitters from a consumption perspective were China (23% of the global total), USA (16%), EU28
31 (12%), and India (6%).

1 Based on fire activity, the global CO₂ emissions from land-use change are estimated as 1.1 ± 0.5
2 GtC in 2014, similar to the 2005-2014 average of 0.9 ± 0.5 GtC yr⁻¹ and the DGVM estimate for
3 2014 of 1.4 ± 0.5 GtC yr⁻¹. However, the estimated annual variability is not generally consistent
4 between methods, except that all methods estimate that variability in E_{LUC} is small relative to the
5 variability from S_{LAND} (Fig. 6a). This could be partly due to the design of the DGVM experiments,
6 which use flux differences between simulations with and without land-cover change, and thus
7 may overestimate variability e.g. due to fires in forest regions where the contemporary forest
8 cover is smaller than pre-industrial cover used in the 'without land cover change' runs. The
9 extrapolated land cover input data for 2013-2014 in the DGVM may also explain part of the
10 discrepancy.

11 3.2.2 Partitioning

12 The atmospheric CO₂ growth rate was 3.9 ± 0.2 GtC in 2014 (1.83 ± 0.09 ppm; Fig. 4; Dlugokencky
13 and Tans, 2015). This is below the 2005-2014 average of 4.4 ± 0.1 GtC yr⁻¹, though the interannual
14 variability in atmospheric growth rate is large.

15 The ocean CO₂ sink was 2.9 ± 0.5 GtC yr⁻¹ in 2014, an increase of 0.1 GtC yr⁻¹ over 2013 according
16 to ocean models. Seven of the eight ocean models produce an increase in the ocean CO₂ sink in
17 2014 compared to 2013, with the last model producing a very small reduction. However, of the
18 two data products available over that period, Rödenbeck et al. (2014) produce a decrease of -0.1
19 GtC yr⁻¹ while Landschützer et al. (2015) produce an increase of 0.2 GtC yr⁻¹. Thus there is no
20 overall consistency in the annual change in the ocean CO₂ sink, although there is an indication of
21 increasing convergence among products for the assessment of multi-year changes, as suggested
22 by the time-series correlations reported in Section 2.4.3 (see also Landschützer et al., 2015). A
23 small increase in the ocean CO₂ in 2014 sink would be consistent with the observed El Niño
24 neutral conditions and continued rising atmospheric CO₂. All estimates suggest an ocean CO₂ sink
25 for 2014 that is larger than the 2005-2014 average of 2.6 ± 0.5 GtC yr⁻¹.

26 The terrestrial CO₂ sink calculated as the residual from the carbon budget was 4.1 ± 0.9 GtC in
27 2014, 1.1 GtC higher than the 3.0 ± 0.8 GtC yr⁻¹ averaged over 2005-2014 (Fig. 4). This is the
28 largest S_{LAND} calculated since 1959, equal to year 2011 (Poulter et al. 2014). In contrast to 2011
29 where La Niña conditions prevailed, the large S_{LAND} in 2014 occurred in neutral El Niño condition.
30 The DGVM model mean produce a sink of 3.6 ± 0.9 GtC in 2014, 0.7 GtC yr⁻¹ over the 2005-2014

1 average (Table 7), smaller but still consistent with observations (Poulter et al., 2014). In the DGVM
2 ensemble, 2014 is the fifth largest S_{LAND} , after 1974, 2011, 2004 and 2000. There is no agreement
3 between models and inversions on the regional origin on the 2014 flux anomaly (Fig. 8).

4 Cumulative emissions for 1870-2014 were 400 ± 20 GtC for E_{FF} , and 145 ± 50 GtC for E_{LUC} based on
5 the bookkeeping method of Houghton et al. (2012) for 1870-1996 and a combination with fire-
6 based emissions for 1997-2014 as described in Section 2.2 (Table 10). The cumulative emissions
7 are rounded to the nearest 5 GtC. The total cumulative emissions for 1870-2014 are 545 ± 55 GtC.
8 These emissions were partitioned among the atmosphere (230 ± 5 GtC based on atmospheric
9 measurements in ice cores of 288 ppm (Section 2.3.1; Joos and Spahni, 2008) and recent direct
10 measurements of 397.2 ppm (Dlugokencky and Tans, 2014)), ocean (155 ± 20 GtC using Khatiwala
11 et al. (2013) prior to 1959 and Table 8 otherwise), and the land (160 ± 60 GtC by the difference).

12 Cumulative emissions for the early period 1750-1869 were 3 GtC for E_{FF} , and about 45 GtC for E_{LUC}
13 (rounded to nearest 5) of which 10 GtC were emitted in the period 1850-1870 (Houghton et al.
14 2012) and 30 GtC were emitted in the period 1750-1850 based on the average of four publications
15 (22 GtC by Pongratz et al. (2009); 15 GtC by van Minnen et al. (2009); 64 GtC by Shevliakova et al.
16 (2009) and 24 GtC by Zaehle et al. (2011)). The growth in atmospheric CO_2 during that time was
17 about 25 GtC, and the ocean uptake about 20 GtC, implying a land uptake of 5 GtC. These
18 numbers have large relative uncertainties but balance within the limits of our understanding.

19 Cumulative emissions for 1750-2014 based on the sum of the two periods above (before rounding
20 to the nearest five GtC) were 405 ± 20 GtC for E_{FF} , and 190 ± 65 GtC for E_{LUC} , for a total of 590 ± 70
21 GtC, partitioned among the atmosphere (255 ± 5 GtC), ocean (170 ± 20 GtC), and the land ($165 \pm$
22 70 GtC).

23 Cumulative emissions through to year 2015 can be estimated based on the 2015 projections of E_{FF}
24 (Section 3.2), the largest contributor, and assuming a constant E_{LUC} of 0.9 GtC. For 1870–2015,
25 these are 555 ± 55 GtC (2040 ± 200 Gt CO_2) for total emissions, with about 75% contribution from
26 E_{FF} (410 ± 20 GtC) and about 25% contribution from E_{LUC} (145 ± 50 GtC). Cumulative emissions
27 since year 1870 are higher than the emissions of 515 [445 to 585] GtC reported in the IPCC
28 (Stocker et al., 2013) because they include an additional 43 GtC from emissions in 2012-2015
29 (mostly from E_{FF}). The uncertainty presented here ($\pm 1\sigma$) is smaller than the range of 90% used by
30 IPCC, but both estimates overlap within their uncertainty ranges.

1 4 Discussion

2 Each year when the global carbon budget is published, each component for all previous years is
3 updated to take into account corrections that are the result of further scrutiny and verification of
4 the underlying data in the primary input data sets. The updates have generally been relatively
5 small and focused on the most recent years, except for land-use change, where they are more
6 significant but still generally within the provided uncertainty range (Fig. 9). The difficulty in
7 accessing land-cover change data to estimate E_{LUC} is the key problem to providing continuous
8 records of emissions in this sector. Current FAO estimates are based on statistics reported at the
9 country level and are not spatially-explicit. Advances in satellite recovery of land-cover change
10 could help to keep track of land-use change through time (Achard et al., 2014; Harris, 2012).
11 Revisions in E_{LUC} for the 2008/2009 budget were the result of the release of FAO 2010, which
12 contained a major update to forest cover change for the period 2000-2005 and provided the data
13 for the following 5 years to 2010 (Fig. 9b). The differences this year could be attributable to both
14 the different data and the different methods. Updates to values for any given year in each
15 component of the global carbon budget were highest at 0.82 GtC yr^{-1} for the atmospheric growth
16 rate (from a one-off correction to year 1979), 0.24 GtC yr^{-1} for fossil fuels and industry, and 0.52
17 GtC yr^{-1} for the ocean CO_2 sink (from a change from one to multiple models; Fig. 9). The update for
18 the residual land CO_2 sink was also large (Fig. 9e), with a maximum value of 0.83 GtC yr^{-1} , directly
19 reflecting revisions in other terms of the budget.

20 Our capacity to separate the carbon budget components can be evaluated by comparing the land
21 CO_2 sink estimated through two approaches: (1) the budget residual (S_{LAND}), which includes errors
22 and biases from all components, and (2) the land CO_2 sink estimate by the DGVM ensemble, which
23 are based on our understanding of processes of how the land responds to increasing CO_2 , climate
24 and variability. Furthermore, the inverse model estimates which formally merge observational
25 constraints with process-based models to close the global budget can provide constraints on the
26 total land flux. These estimates are generally close (Fig. 6), both for the mean and for the
27 interannual variability. The annual estimates from the DGVM over 1959 to 2014 correlate with the
28 annual budget residual with $r = 0.71$ (Section 2.5.2; Fig. 6). The DGVMs produce a decadal mean
29 and standard deviation across models of $3.0 \pm 0.4 \text{ GtC yr}^{-1}$ for the period 2005-2014, fully
30 consistent with the estimate of $3.0 \pm 0.8 \text{ GtC yr}^{-1}$ produced with the budget residual (Table 7).
31 New insights into total surface fluxes arise from the comparison with the atmospheric inversions

1 and their regional breakdown already provide a semi-independent way to validate the results. The
2 comparison shows a first-order consistency between inversions and process models but with a lot
3 of discrepancies, particularly for the allocation of the mean land sink between the tropics and the
4 Northern hemisphere. Understanding these discrepancies and further analysis of regional carbon
5 budgets would provide additional information to quantify and improve our estimates, as has been
6 undertaken by the project REgional Carbon Cycle Assessment and Processes (RECAPP; Canadell et
7 al., 2012-2013).

8 Annual estimates of each component of the global carbon budgets have their limitations, some of
9 which could be improved with better data and/or better understanding of carbon dynamics. The
10 primary limitations involve resolving fluxes on annual time scales and providing updated estimates
11 for recent years for which data-based estimates are not yet available or only beginning to emerge.
12 Of the various terms in the global budget, only the burning of fossil fuels and atmospheric growth
13 rate terms are based primarily on empirical inputs supporting annual estimates in this carbon
14 budget. The data on fossil fuels and industry are based on survey data in all countries. The other
15 terms can be provided on an annual basis only through the use of models. While these models
16 represent the current state of the art, they provide only simulated changes in primary carbon
17 budget components. For example, the decadal trends in global ocean uptake and the interannual
18 variations associated with El Niño-Southern Ocean Oscillation (e.g. ENSO) are not directly
19 constrained by observations, although many of the processes controlling these trends are
20 sufficiently well known that the model-based trends still have value as benchmarks for further
21 validation. Data-based products for the ocean CO₂ sink provide new ways to evaluate the model
22 results, and could be used directly as data become more rapidly available and methods for
23 creating such products improve. However, **there are still large discrepancies among data-based**
24 **estimates, in large part due to the lack of routine data sampling, that preclude their direct use for**
25 **now (see Rödenbeck et al., 2015).** Estimates of land-use emissions and their year-to-year
26 variability have even larger uncertainty, and much of the underlying data are not available as an
27 annual update. Efforts are underway to work with annually available satellite area change data or
28 FAO reported data in combination with fire data and modelling to provide annual updates for
29 future budgets. The best resolved changes are in atmospheric growth (G_{ATM}), fossil fuel emissions
30 (E_{FF}), and by difference, the change in the sum of the remaining terms ($S_{OCEAN} + S_{LAND} - E_{LUC}$). The
31 variations from year-to-year in these remaining terms are largely model-based at this time.

1 Further efforts to increase the availability and use of annual data for estimating the remaining
2 terms with annual to decadal resolution are especially needed.

3 Our approach also depends on the reliability of the energy and land-cover change statistics
4 provided at the country level, and are thus potentially subject to biases. Thus it is critical to
5 develop multiple ways to estimate the carbon balance at the global and regional level, including
6 estimates from the inversion of atmospheric CO₂ concentration, the use of other oceanic and
7 atmospheric tracers, and the compilation of emissions using alternative statistics (e.g. sectors). It
8 is also important to challenge the consistency of information across observational streams, for
9 example to contrast the coherence of temperature trends with those of CO₂ sink trends. Multiple
10 approaches ranging from global to regional scale would greatly help increase confidence and
11 reduce uncertainty in CO₂ emissions and their fate.

12 **5 Conclusions**

13 The estimation of global CO₂ emissions and sinks is a major effort by the carbon cycle research
14 community that requires a combination of measurements and compilation of statistical estimates
15 and results from models. The delivery of an annual carbon budget serves two purposes. First,
16 there is a large demand for up-to-date information on the state of the anthropogenic perturbation
17 of the climate system and its underpinning causes. A broad stakeholder community relies on the
18 data sets associated with the annual carbon budget including scientists, policy makers, businesses,
19 journalists, and the broader society increasingly engaged in adapting to and mitigating human-
20 driven climate change. Second, over the last decade we have seen unprecedented changes in the
21 human and biophysical environments (e.g. increase in the growth of fossil fuel emissions, ocean
22 temperatures, and strength of the land sink), which call for more frequent assessments of the
23 state of the Planet, and by implications a better understanding of the future evolution of the
24 carbon cycle, and the requirements for climate change mitigation and adaptation. Both the ocean
25 and the land surface presently remove a large fraction of anthropogenic emissions. Any significant
26 change in the function of carbon sinks is of great importance to climate policymaking, as they
27 affect the excess carbon dioxide remaining in the atmosphere and therefore the compatible
28 emissions for any climate stabilization target. Better constraints of carbon cycle models against
29 contemporary data sets raises the capacity for the models to become more accurate at future
30 projections.

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

7 This paper via 'living data' will help to keep track of new budget updates. The evolution over time
8 of the carbon budget is now a key indicator of the anthropogenic perturbation of the climate
9 system, and its annual delivery joins a set of other climate indicators to monitor the evolution of
10 human-induced climate change, such as the annual updates on the global surface temperature,
11 sea level rise, minimum Arctic sea ice extent among others.

12 **Data access**

13 The data presented here are made available in the belief that their wide dissemination will lead to
14 greater understanding and new scientific insights of how the carbon cycle works, how humans are
15 altering it, and how we can mitigate the resulting human-driven climate change. The free
16 availability of these data does not constitute permission for publication of the data. For research
17 projects, if the data are essential to the work, or if an important result or conclusion depends on
18 the data, co-authorship may need to be considered. Full contact details and information on how
19 to cite the data are given at the top of each page in the accompanying database, and summarised
20 in Table 2.

21 The accompanying database includes two Excel files organised in the following spreadsheets
22 (accessible with the free viewer <http://www.microsoft.com/en-us/download/details.aspx?id=10>):

23 File Global_Carbon_Budget_2015.xlsx includes:

- 24 1. Summary
- 25 2. The global carbon budget (1959-2014);
- 26 3. Global CO₂ emissions from fossil fuels and cement production by fuel type, and the per-capita
27 emissions (1959-2014);
- 28 4. CO₂ emissions from land-use change from the individual methods and models (1959-2014);
- 29 5. Ocean CO₂ sink from the individual ocean models and data products (1959-2014);
- 30 6. Terrestrial residual CO₂ sink from the DGVMs (1959-2014);

1 7. Additional information on the carbon balance prior to 1959 (1750-2014).

2 File National_Carbon_Emissions_2015.xlsx includes:

3 1. Summary

4 2. Territorial country CO₂ emissions from fossil fuels and industry (1959-2014) from CDIAC,
5 extended to 2014 using BP data;

6 3. Territorial country CO₂ emissions from fossil fuels and industry (1959-2014) from CDIAC with
7 UNFCCC data overwritten where available, extended to 2014 using BP data;

8 4. Consumption country CO₂ emissions from fossil fuels and industry and emissions transfer
9 from the international trade of goods and services (1990-2013) using CDIAC/UNFCCC data
10 (worksheet 3 above) as reference;

11 5. Emissions transfers (Consumption minus territorial emissions; 1990-2013);

12 6. Country definitions.

13 National emissions data are also available from the Global Carbon Atlas (globalcarbonatlas.org).

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Submitted

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

Unit 1	Unit 2	Conversion	Source
GtC (gigatonnes of carbon)	ppm (parts per million) ^a	2.12 ^b	Ballantyne et al. (2012)
GtC (gigatonnes of carbon)	PgC (petagrammes of carbon)	1	SI unit conversion
GtCO ₂ (gigatonnes of carbon dioxide)	GtC (gigatonnes of carbon)	3.664	44.01/12.011 in mass equivalent
GtC (gigatonnes of carbon)	MtC (megatonnes of carbon)	1000	SI unit conversion

4 ^a Measurements of atmospheric CO₂ concentration have units of dry-air mole fraction. 'ppm' is an
5 abbreviation for micromole/mol, dry air.

6 ^bthe use of a factor of 2.12 assumes that all the atmosphere is well mixed within one year. In reality, only
7 the troposphere is well mixed and the growth rate of CO₂ in the less well-mixed stratosphere is not
8 measured by sites from the NOAA network. Using a factor of 2.12 makes the approximation that the
9 growth rate of CO₂ in the stratosphere equals that of the troposphere on a yearly basis.

10

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

Component	Primary reference
Global emissions from fossil fuels and industry (E_{FF}), total and by fuel type	Boden et al. (2015; CDIAC: cdiac.ornl.gov/trends/emis/meth_reg.html)
National territorial emissions from fossil fuels and industry (E_{FF})	CDIAC source: Boden et al. (2015; CDIAC: cdiac.ornl.gov/trends/emis/meth_reg.html) UNFCCC source: (2015; http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/8108.php ; accessed May 2015)
National consumption-based emissions from fossil fuels and industry (E_{FF}) by country (consumption)	Peters et al. (2011b) updated as described in this paper
Land-use change emissions (E_{LUC})	Houghton et al. (2012) combined with Giglio et al. (2013)
Atmospheric CO ₂ growth rate (G_{ATM})	Dlugokencky and Tans (2015; NOAA/ESRL: www.esrl.noaa.gov/gmd/ccgg/trends/global ; accessed October 12 2015)
Ocean and land CO ₂ sinks (S_{OCEAN} and S_{LAND})	This paper for S_{OCEAN} and S_{LAND} and references in Table 6 for individual models.

- 1 **Table 3.** Main methodological changes in the global carbon budget since first publication. Unless specified below, the methodology was identical to that
 2 described in the current paper. Furthermore, methodological changes introduced in one year are kept for the following years unless noted. Empty cells mea
 3 there were no methodological changes introduced that year.

Publication year ^a	Fossil fuel emissions			LUC emissions	Reservoirs			Uncertainty & other changes
	Global	Country (territorial)	Country (consumption)		Atmosphere	Ocean	Land	
2006 Raupach et al. (2007)		Split in regions						
2007 Canadell et al. (2007)				E_{LUC} based on FAO-FRA 2005; constant E_{LUC} for 2006	1959-1979 data from Mauna Loa; data after 1980 from global average	Based on one ocean model tuned to reproduced observed 1990s sink		$\pm 1\sigma$ provided for all components
2008 (online)				Constant E_{LUC} for 2007				
2009 Le Quéré et al. (2009)		Split between Annex B and non-Annex B	Results from an independent study discussed	Fire-based emission anomalies used for 2006-2008		Based on four ocean models normalised to observations with constant delta	First use of five DGVMs to compare with budget residual	
2010 Friedlingstein et al. (2010)	Projection for current year based on GDP	Emissions for top emitters		E_{LUC} updated with FAO-FRA 2010				
2011 Peters et al. (2012b)			Split between Annex B and non-Annex B					
2012 Le Quéré et al. (2013) Peters et al. (2013)		129 countries from 1959	129 countries and regions from 1990-2010 based on GTAP8.0	E_{LUC} for 1997-2011 includes interannual anomalies from fire-based emissions	All years from global average	Based on 5 ocean models normalised to observations with ratio	Ten DGVMs available for S_{LAND} ; First use of four models to compare with E_{LUC}	
2013 Le Quéré et al. (2014)		250 countries ^b	134 countries and regions 1990-2011 based on GTAP8.1, with detailed estimates for years 1997, 2001, 2004, and 2007	E_{LUC} for 2012 estimated from 2001-2010 average		Based on six models compared with two data-products to year 2011	Coordinated DGVM experiments for S_{LAND} and E_{LUC}	Confidence levels; cumulative emissions; budget from 1750
2014 Le Quéré et al. (2015)	Three years of BP data	Three years of BP data	Extended to 2012 with updated GDP data	E_{LUC} for 1997-2013 includes interannual anomalies from fire-based emissions		Based on seven models compared with three data-products to year 2013	Based on ten models	Inclusion of breakdown of the sinks in three latitude bands and comparison with three atmospheric inversions
2015 (this study)		National emissions from UNFCCC extended to 2014 also provided (along with CDIAC)	Detailed estimates introduced for 2011 based on GTAP9			Based on eight models compared with two data-products to year 2014	Based on ten models with assessment of minimum realism	The decadal uncertainty for the DGVM ensemble mean now uses $\pm 1\sigma$ of the decadal spread across models

- 4 ^aThe naming convention of the budgets has changed. Up to and including 2010, the budget year (Carbon Budget 2010) represented the latest year of the data. From 2012,
 5 the budget year (Carbon Budget 2012) refers to the initial publication year.

- 6 ^bThe CDIAC database has about 250 countries, but we show data for about 216 countries since we aggregate and disaggregate some countries to be consistent with
 7 current country definitions (see Sect. 2.1.1 for more details).

1 **Table 4.** Data sources used to compute each component of the global carbon budget.

Component	Process	Data source	Data reference
E_{FF} (global and CDIAC national)	Fossil fuel combustion and gas flaring	UN Statistics Division to 2011	UN (2014a, b)
		BP for 2012-2014	BP (2015)
	Cement production	US Geological Survey	van Oss (2015) US Geological Survey (2015)
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	FAO (2010)
			FAOSTAT (2010)
Interannual variability from peat fires and climate – land management interactions (1997-2013)	Global Fire Emissions Database (GFED4)	Giglio et al., (2013)	
G_{ATM}	Change in atmospheric CO ₂ concentration	1959-1980: CO ₂ Program at Scripps Institution of Oceanography and other research groups	Keeling et al. (1976)
		1980-2015: US National Oceanic and Atmospheric Administration Earth System Research Laboratory	Dlugokencky and Tans (2015) 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)
			Keeling et al. (2011) McNeil et al. (2003) Mikaloff Fletcher et al. (2006) as assessed by the IPCC in Denman et al. (2007)
	Impact of increasing atmospheric CO ₂ , climate and variability	Ocean models	Table 6
S_{LAND}	Response of land vegetation to: Increasing atmospheric CO ₂ concentration Climate and variability Other environmental changes	Budget residual	

2

- 1 **Table 5.** Comparison of the processes included in the E_{LUC} of the global carbon budget and the
 2 DGVMs. See Table 6 for model references. All models include deforestation and forest regrowth
 3 after abandonment of agriculture (or from afforestation activities on agricultural land).

	Bookkeeping	CLM4.5BGC	ISAM	JSBACH	JULES	LPJ-GUESS	LPJ	LPJmL	OCNv1.r240	ORCHIDEE	VISIT
Wood harvest and forest degradation ^a	yes	yes	yes	yes	no	no	no	no	yes	no	yes ^b
Shifting cultivation	yes	yes	no	yes	no	no	no	no	no	no	yes
Cropland harvest	yes	yes	yes	yes ^c	no	yes	no	yes	yes	yes	yes
Peat fires	no	yes	no	no	no	no	no	no	no	no	no
Fire simulation and/or suppression	for US only	yes	no	yes	no	yes	yes	yes	no	no	yes
Climate and variability	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
CO ₂ fertilisation	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Carbon-nitrogen interactions, including N deposition	no	yes	yes	no	no	no	no	no	yes	no	no

- 4 ^aRefers to the routine harvest of established managed forests rather than pools of harvested products. ^bWood stems
 5 are harvested according to the land-use data. ^cCarbon from crop harvest is entirely transferred into the litter pools.

1 **Table 6.** References for the process models and data products included in Figs. 6-8.

Model/data name	Reference	Change from Le Quéré et al. (2015)
<i>Dynamic global vegetation models</i>		
CLM4.5BGC ^a	Oleson et al. (2013)	No change
ISAM	Jain et al. (2013) ^b	We accounted for crop harvest for C3 and C4 crops based on Arora and Boer (2005) and agricultural soil carbon loss due to tillage (Jain et al., 2005)
JSBACH	Reick et al. (2013) ^c	Not applicable (first use of this model)
JULES ^e	Clarke et al. (2011) ^e	Updated JULES version 4.3 compared to v3.2 for last years budget. A number of small code changes but no change in major science sections with the exception to an update in the way litter flux is calculated.
LPJ-GUESS	Smith et al. (2014a)	Implementation of C/N interactions in soil and vegetation, including a complete update of the soil organic matter scheme
LPJ ^f	Sitch et al. (2003)	No change
LPJmL	Bondeau et al. (2007) ^g	Not applicable (first use of this model)
OCNv1.r240	Zaehle et al. (2011) ^h	Revised photosynthesis parameterisation allowing for temperature acclimation as well as cold and heat effects on canopy processes. Revised grassland phenology. Included wood harvest as a driver to simulate harvest and post-harvest regrowth. Using Hurtt land-use data set
ORCHIDEE	Krinner et al. (2005)	Revised parameters values for photosynthetic capacity for boreal forests (following assimilation of FLUXNET data), updated parameters values for stem allocation, maintenance respiration and biomass export for tropical forests (based on literature) and, CO2 down-regulation process added to photosynthesis.
VISIT	Kato et al. (2013) ⁱ	No change
<i>Data products for land-use change emissions</i>		
Bookkeeping	Houghton et al. (2012)	No change
Fire-based emissions	van der Werf et al. (2010)	No change
<i>Ocean biogeochemistry models</i>		
NEMO-PlankTOM5	Buitenhuis et al. (2010) ^j	No change
NEMO-PISCES (IPSL) ^k	Aumont and Bopp (2006)	No change
CCSM-BEC	Doney et al. (2009)	No change; small differences in the mean flux are caused by a change in how global and annual means were computed
MICOM-HAMOCC (NorESM-OC)	Assmann et al. (2010) ^{l,m}	Revised light penetration formulation and parameters for ecosystem module, revised salinity restoring scheme enforcing salt conservation, new scheme enforcing global freshwater balance, and model grid changed from displaced pole to tripolar
MPIOM-HAMOCC	Ilyina et al. (2013)	No change
NEMO-PISCES (CNRM)	Séférian et al. (2013) ⁿ	No change
CSIRO	Oke et al. (2013)	No change

MITgcm-REcoM2	Hauck et al. (2013) ^o	Not applicable (first use of this model)
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Data products for ocean CO₂ flux

Landschützer ^p	Landschützer et al. (2015)	No change
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Jena CarboScope ^p	Rödenbeck et al. (2014)	Updated to version oc_1.2gcp2015
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Atmospheric inversions for total CO₂ fluxes (land-use-change + land + ocean CO₂ fluxes)

CarbonTracker	Peters et al. (2010)	Updated to version CTE2015. Updates include using CO ₂ observations from obspack_co2_1_GLOBALVIEWplus_v1.0_2015-07-30 (NOAA/ESRL, 2015b), prior SiBCASA biosphere and fire fluxes on 3 hourly resolution and fossil fuel emissions for 2010-2014 scaled to updated global totals.
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Jena CarboScope	Rödenbeck et al. (2003)	Updated to version s81_v3.7
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MACC ^q	Chevallier et al. (2005)	Updated to version 14.2. Updates include a change of the convection scheme and a revised data selection.
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- 1
2 ^aCommunity Land Model 4.5
3 ^bSee also El-Masri et al. (2013)
4 ^cSee also Goll et al (2015)
5 ^dJoint UK Land Environment Simulator
6 ^eSee also Best et al. (2011)
7 ^fLund-Potsdam-Jena
8 ^gThe LPJmL (Lund-Potsdam-Jena managed Land) version used includes also developments described in Rost et al.
9 (2008; river routing and irrigation), Fader et al. (2010; agricultural management), Biemans et al. (2011; reservoir
10 management), Shapfhoff et al. (2013; permafrost and 5 layer hydrology), and Waha et al. (2012; sowing data) (sowing
11 dates)
12 ^hSee also Zaehle et al. (2010) and Friend et al. (2010)
13 ⁱsee also Ito and Inatomi (2012)
14 ^jWith no nutrient restoring below the mixed layer depth
15 ^kReferred to as LSCE in previous carbon budgets
16 ^lWith updates to the physical model as described in Tjiputra et al. (2013)
17 ^mFurther information (e.g., physical evaluation) for these models can be found in Danabasoglu et al. (2014)
18 ⁿusing winds from Atlas et al. (2011)
19 ^oA few changes have been applied to the ecosystem model: (1) The constant Fe:C ratio was substituted by a constant
20 Fe:N ratio. (2) A sedimentary iron source was implemented. (3) the following parameters were changed:
21 *CHL_N_max*=3.78, *Fe2N* = 0.033, *deg_CHL_d* = 0.1, *Fe2N_d* = 0.033, *ligandStabConst*=200, *constantIronSolubility* =
22 0.02
23 ^pupdates using SOCATv3 plus new 2012-2014 data
24 ^qThe MACCv14.2 CO₂ inversion system, initially described by Chevallier et al. (2005), relies on the global tracer
25 transport model LMDZ (see also Supplementary Material Chevallier, 2015; Hourdin et al., 2006).
26

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1 **Table 7.** Comparison of results from the bookkeeping method and budget residuals with results from the DGVMs and inverse estimates for the
 2 periods 1960-1969, 1970-1979, 1980-1989, 1990-1999, 2000-2009, last decade and last year available. All values are in GtC yr⁻¹. The DGVM
 3 uncertainties represents $\pm 1\sigma$ of the decadal or annual (for 2014 only) estimates from the ten individual models, for the inverse models all three
 4 results are given where available.
 5

	Mean (GtC yr ⁻¹)						
	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2005-2014	2014
<i>Land-use change emissions (E_{LUC})</i>							
Bookkeeping method	1.5 ± 0.5	1.3 ± 0.5	1.4 ± 0.5	1.6 ± 0.5	1.0 ± 0.5	0.9 ± 0.5	1.1 ± 0.5
DGVMs ^a	1.2 ± 0.4	1.2 ± 0.4	1.3 ± 0.4	1.2 ± 0.4	1.2 ± 0.4	1.4 ± 0.4	1.4 ± 0.5
<i>Residual terrestrial sink (S_{LAND})</i>							
Budget residual	1.7 ± 0.7	1.7 ± 0.8	1.6 ± 0.8	2.6 ± 0.8	2.4 ± 0.8	3.0 ± 0.8	4.1 ± 0.9
DGVMs ^a	1.1 ± 0.6	2.1 ± 0.3	1.7 ± 0.4	2.3 ± 0.3	2.7 ± 0.4	3.0 ± 0.5	3.6 ± 0.9
<i>Total land fluxes ($S_{LAND} - E_{LUC}$)</i>							
Budget ($E_{FF} - G_{ATM} - S_{OCEAN}$)	0.2 ± 0.5	0.4 ± 0.6	0.2 ± 0.6	1.0 ± 0.6	1.5 ± 0.6	2.1 ± 0.7	3.0 ± 0.7
DGVMs ^a	-0.1 ± 0.6	0.9 ± 0.4	0.5 ± 0.5	1.1 ± 0.5	1.5 ± 0.4	1.6 ± 0.4	2.3 ± 0.9
Inversions (CTE2015/Jena CarboScope/MACC)*	—/—/—	—/—/—	-/0.3*/0.8*	-/1.1*/1.8*	-/1.6*/2.4*	2.0*/2.0*/3.3*	2.8*/2.6*/4.2*

6 ^aNote that the decadal uncertainty calculation for the DGVMs is smaller here compared to previous Global Carbon Budgets because it uses $\pm 1\sigma$ of the
 7 decadal estimates for the DGVMs, compared to the average of the annual $\pm 1\sigma$ estimates in previous years. It thus represents the true model range for their
 8 decadal estimates. This change was introduced to be consistent with the decadal uncertainty calculations in Table 8

9 *Estimates are not corrected for the influence of river fluxes, which would reduce the fluxes by 0.45 GtC yr⁻¹ when neglecting the anthropogenic influence on land (Section
 10 7.2.2). CTE2015 refers to Peters et al. (2010), Jena CarboScope to Rödenbeck et al. (2014) and MACC to Chevallier et al. (2005); see Table 6.

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1 **Table 8.** Decadal mean in the five components of the anthropogenic CO₂ budget for the periods 1960-1969, 1970-1979, 1980-1989, 1990-1999,
 2 2000-2009, last decade and last year available. All values are in GtC yr⁻¹. All uncertainties are reported as ±1σ. A data set containing data for
 3 each year during 1959-2014 is available on <http://cdiac.ornl.gov/GCP/carbonbudget/2015/>. Please follow the terms of use and cite the
 4 original data sources as specified on the data set.

	Mean (GtC yr ⁻¹)						
	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2005-2014	2014
<i>Emissions</i>							
Fossil fuels and industry (E _{FF})	3.1 ± 0.2	4.7 ± 0.2	5.5 ± 0.3	6.4 ± 0.3	7.8 ± 0.4	9.0 ± 0.5	9.8 ± 0.5
Land-use change emissions (E _{LUC})	1.5 ± 0.5	1.3 ± 0.5	1.4 ± 0.5	1.6 ± 0.5	1.0 ± 0.5	0.9 ± 0.5	1.1 ± 0.5
<i>Partitioning</i>							
Atmospheric growth rate (G _{ATM})	1.7 ± 0.1	2.8 ± 0.1	3.4 ± 0.1	3.1 ± 0.1	4.0 ± 0.1	4.4 ± 0.1	3.9 ± 0.2
Ocean sink (S _{OCEAN})*	1.1 ± 0.5	1.5 ± 0.5	2.0 ± 0.5	2.2 ± 0.5	2.3 ± 0.5	2.6 ± 0.5	2.9 ± 0.5
Residual terrestrial sink (S _{LAND})	1.7 ± 0.7	1.7 ± 0.8	1.6 ± 0.8	2.6 ± 0.8	2.4 ± 0.8	3.0 ± 0.8	4.1 ± 0.9

5 *The uncertainty in S_{OCEAN} for the 1990s is directly based on observations, while that for other decades combines the uncertainty from observations with the model spread
 6 (Sect. 2.4.3).

1 **Table 9.** Actual CO₂ emissions from fossil fuels and industry (E_{FF}) compared to projections made
 2 the previous year based on world GDP (IMF October 2015) and the fossil fuel intensity of GDP (I_{FF})
 3 based on subtracting the CO₂ and GDP growth rates. The ‘Actual’ values are the latest estimate
 4 available and the ‘Projected’ value for 2015 refers to those presented in this paper. A correction
 5 for leap years is applied (Section 2.1.3).

6

	E _{FF}		GDP		I _{FF}	
	Projected	Actual	Projected	Actual	Projected	Actual
2009 ^a	-2.8%	-0.5%	-1.1%	-0.4%	-1.7%	-0.9%
2010 ^b	>3%	4.9%	4.8%	5.2%	>-1.7%	-0.3%
2011 ^c	3.1±1.5%	3.2%	4.0%	3.9%	-0.9±1.5%	-0.7%
2012 ^d	2.6% (1.9 to 3.5)	2.2%	3.3%	3.2%	-0.7%	-1.0%
2013 ^e	2.1% (1.1 to 3.1)	2.3%	2.9%	3.2%	-0.8%	-0.9%
2014 ^f	2.5% (1.3 to 3.5)	0.6%	3.3%	3.4%	-0.7%	-2.8%
2015 ^g	-0.6% (-1.6 to 0.5)	--	3.1%	--	-3.7%	--

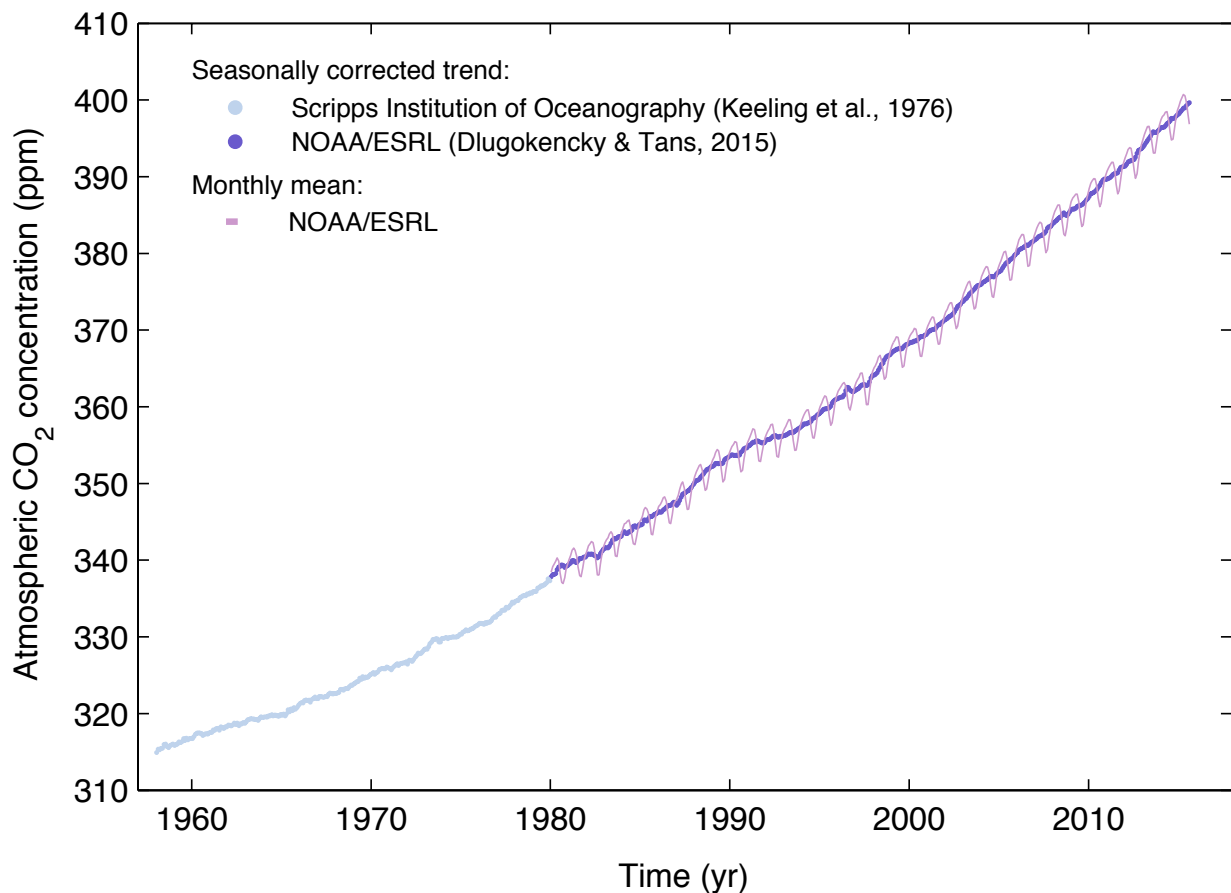
7 ^aLe Quéré et al. (2009). ^bFriedlingstein et al. (2010). ^cPeters et al. (2013). ^dLe Quéré et al. (2013). ^eLe Quéré et al.
 8 (2014). ^fFriedlingstein et al. (2014) and (Le Quéré et al., 2015). ^gThis study.

9

1 **Table 10.** Cumulative CO₂ emissions for the periods 1750-2014, 1870-2014 and 1870-2015 in
 2 gigatonnes of carbon (GtC). We also provide the 1850-2005 time-period used in a number of
 3 model evaluation publications. All uncertainties are reported as $\pm 1\sigma$. All values are rounded to
 4 nearest 5 GtC as in Stocker et al. (2013), reflecting the limits of our capacity to constrain
 5 cumulative estimates. Thus some columns will not exactly balance because of rounding errors.

Units of GtC	1750-2014	1850-2005	1870-2014	1870-2015
<i>Emissions</i>				
Fossil fuels and industry (E_{FF})	405 \pm 20	320 \pm 15	400 \pm 20	410 \pm 20*
Land-use change emissions (E_{LUC})	190 \pm 65	150 \pm 55	145 \pm 50	145 \pm 50*
Total emissions	590 \pm 70	470 \pm 55	545 \pm 55	555 \pm 55*
<i>Partitioning</i>				
Atmospheric growth rate (G_{ATM})	255 \pm 5	195 \pm 5	230 \pm 5	
Ocean sink (S_{OCEAN})	170 \pm 20	160 \pm 20	155 \pm 20	
Residual terrestrial sink (S_{LAND})	165 \pm 70	115 \pm 60	160 \pm 60	

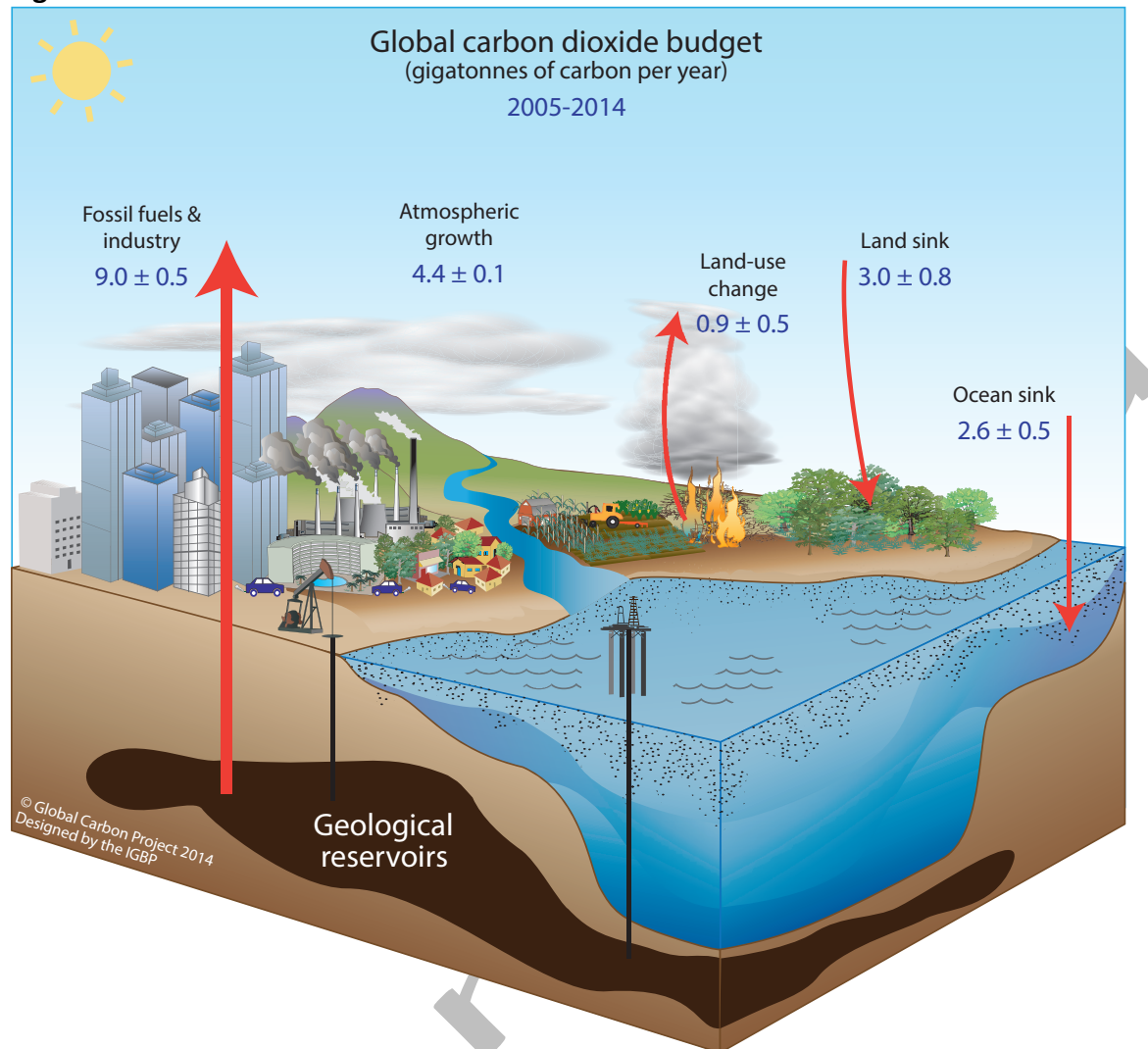
6 *The extension to year 2015 uses the emissions projections for fossil fuels and industry for 2015 of 9.7 GtC (Sect. 3.2)
 7 and assumes a constant E_{LUC} flux (Sect. 2.2).
 8

1 **Fig. 1**

2
3
4 **Figure 1.** Surface average atmospheric CO₂ concentration, deseasonalised (ppm). The 1980-2015
5 monthly data are from NOAA/ESRL (Dlugokencky and Tans, 2015) and is based on an average of
6 direct atmospheric CO₂ measurements from multiple stations in the marine boundary layer
7 (Masarie and Tans, 1995). The 1958-1979 monthly data are from the Scripps Institution of
8 Oceanography, based on an average of direct atmospheric CO₂ measurements from the Mauna
9 Loa and South Pole stations (Keeling et al., 1976). To take into account the difference of mean CO₂
10 between the NOAA/ESRL and the Scripps station networks used here, the Scripps surface average
11 (from two stations) was harmonised to match the NOAA/ESRL surface average (from multiple
12 stations) by adding the mean difference of 0.542 ppm, calculated here from overlapping data
13 during 1980-2012. The mean seasonal cycle is also shown from 1980.

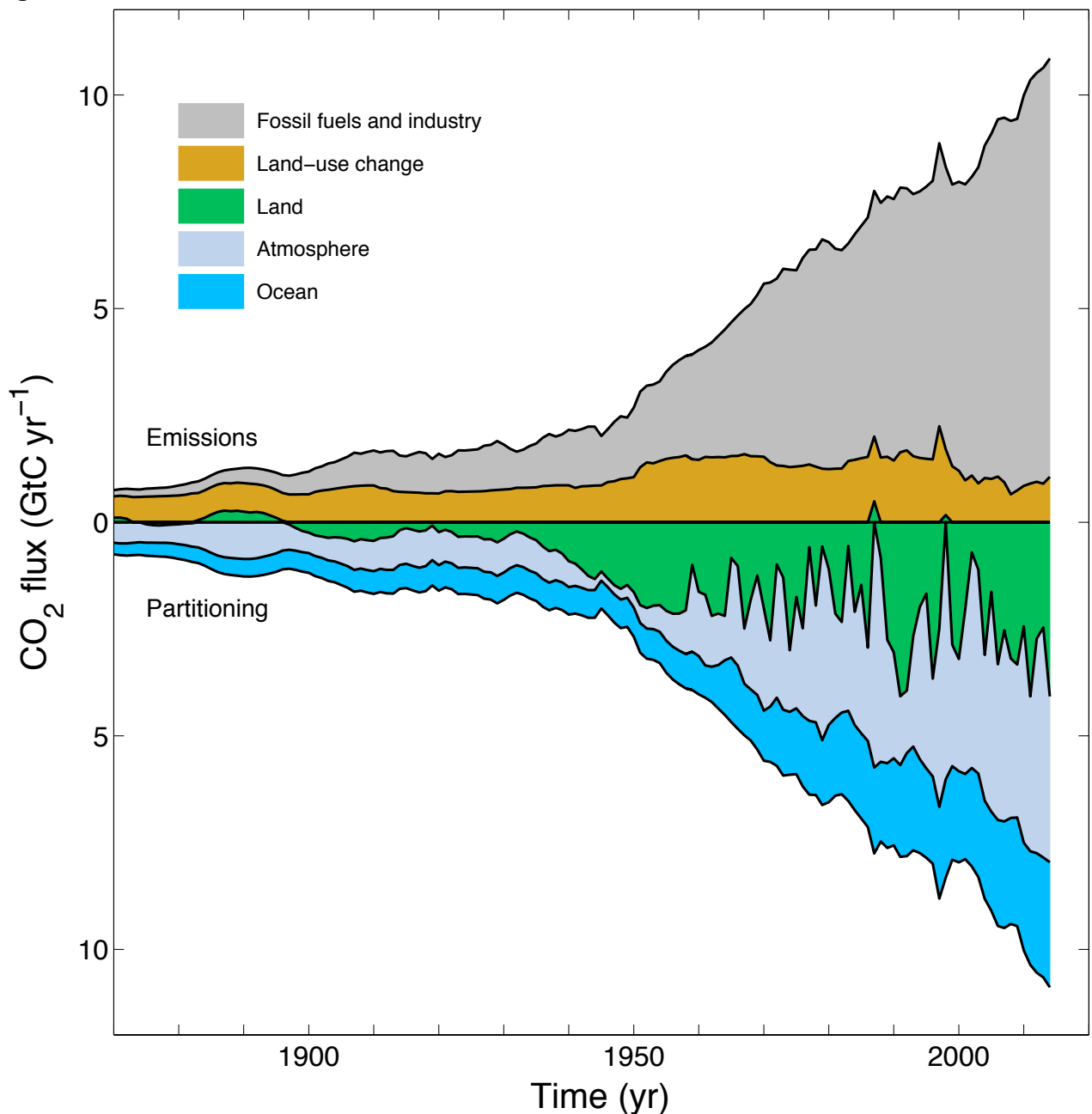
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15

1 **Fig. 2**



2
3
4 **Figure 2.** Schematic representation of the overall perturbation of the global carbon cycle caused
5 by anthropogenic activities, averaged globally for the decade 2005-2014. The arrows represent
6 emission from fossil fuels and industry (E_{FF}); emissions from deforestation and other land-use
7 change (E_{LUC}); the growth of carbon in the atmosphere (G_{ATM}) and the uptake of carbon by the
8 ‘sinks’ in the ocean (S_{OCEAN}) and land (S_{LAND}) reservoirs. All fluxes are in units of $GtC\ yr^{-1}$, with
9 uncertainties reported as $\pm 1\sigma$ (68% confidence that the real value lies within the given interval) as
10 described in the text. This figure is an update of one prepared by the International Geosphere
11 Biosphere Programme for the GCP, first presented in Le Quéré (2009).

12

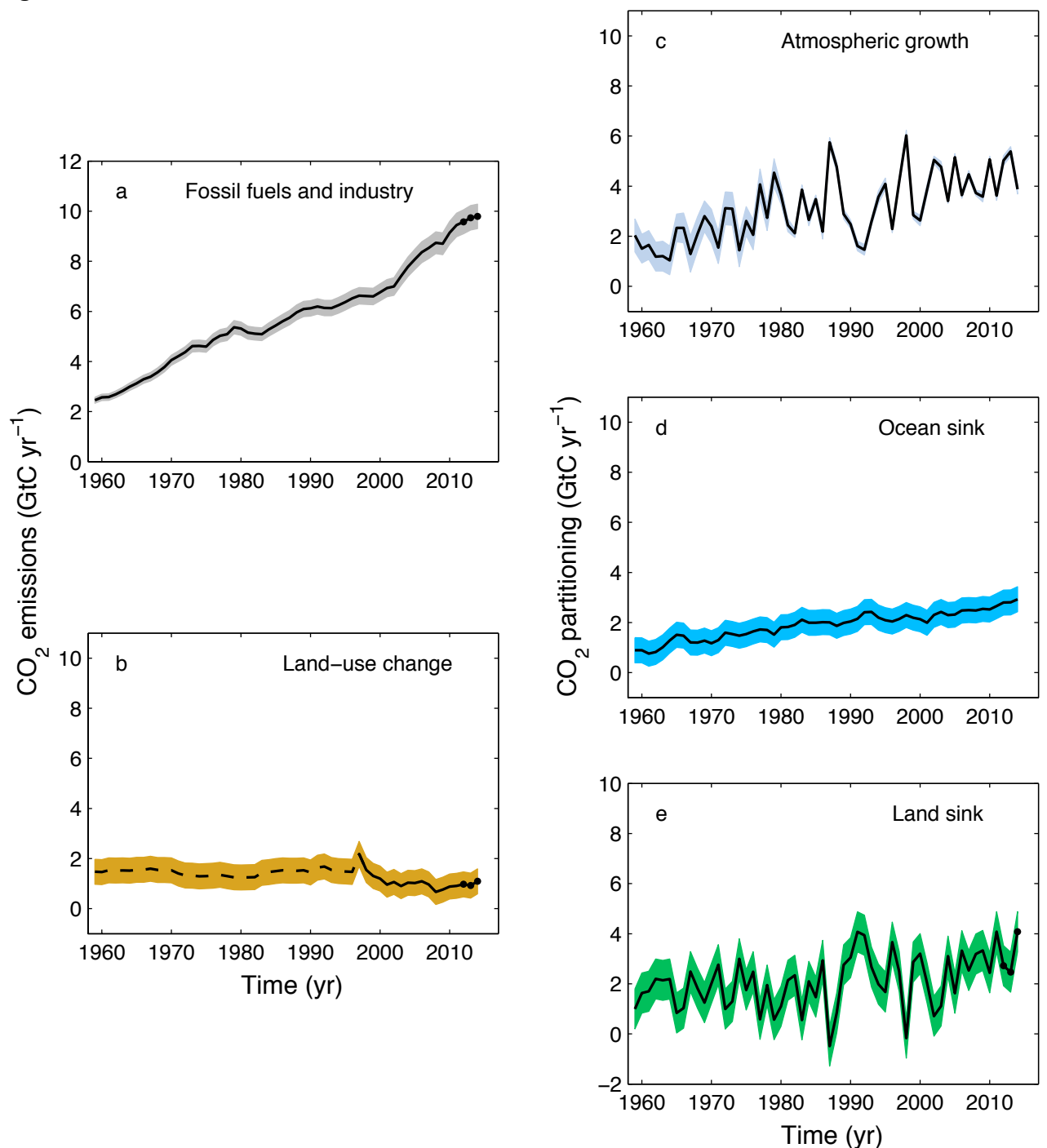
1 **Fig. 3**

2
3 **Figure 3.** Combined components of the global carbon budget illustrated in Fig. 2 as a function of
4 time, for emissions from fossil fuels and industry (E_{FF} ; grey) and emissions from land-use change
5 (E_{LUC} ; brown), as well as their partitioning among the atmosphere (G_{ATM} ; light blue), land (S_{LAND} ;
6 green) and oceans (S_{OCEAN} ; dark blue). All time-series are in $GtC\ yr^{-1}$. G_{ATM} and S_{OCEAN} (and by
7 construction also S_{LAND}) prior to 1959 are based on different methods. The primary data sources
8 for fossil fuels and industry are from Boden et al. (2013), with uncertainty of about $\pm 5\%$ ($\pm 1\sigma$);
9 land-use change emissions are from Houghton et al. (2012) with uncertainties of about $\pm 30\%$;
10 atmospheric growth rate prior to 1959 is from Joos and Spahni (2008) with uncertainties of about

1 $\pm 1-1.5 \text{ GtC decade}^{-1}$ or $\pm 0.1-0.15 \text{ GtC yr}^{-1}$ (Bruno and Joos, 1997), and from Dlugokencky and Tans
2 (2015) from 1959 with uncertainties of about $\pm 0.2 \text{ GtC yr}^{-1}$; the ocean sink prior to 1959 is from
3 Khatiwala et al. (2013) with uncertainty of about $\pm 30 \%$, and from this study from 1959 with
4 uncertainties of about $\pm 0.5 \text{ GtC yr}^{-1}$; and the residual land sink is obtained by difference (Eq. 8),
5 resulting in uncertainties of about $\pm 50 \%$ prior to 1959 and $\pm 0.8 \text{ GtC yr}^{-1}$ after that. See the text for
6 more details of each component and their uncertainties.

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1 **Fig. 4**

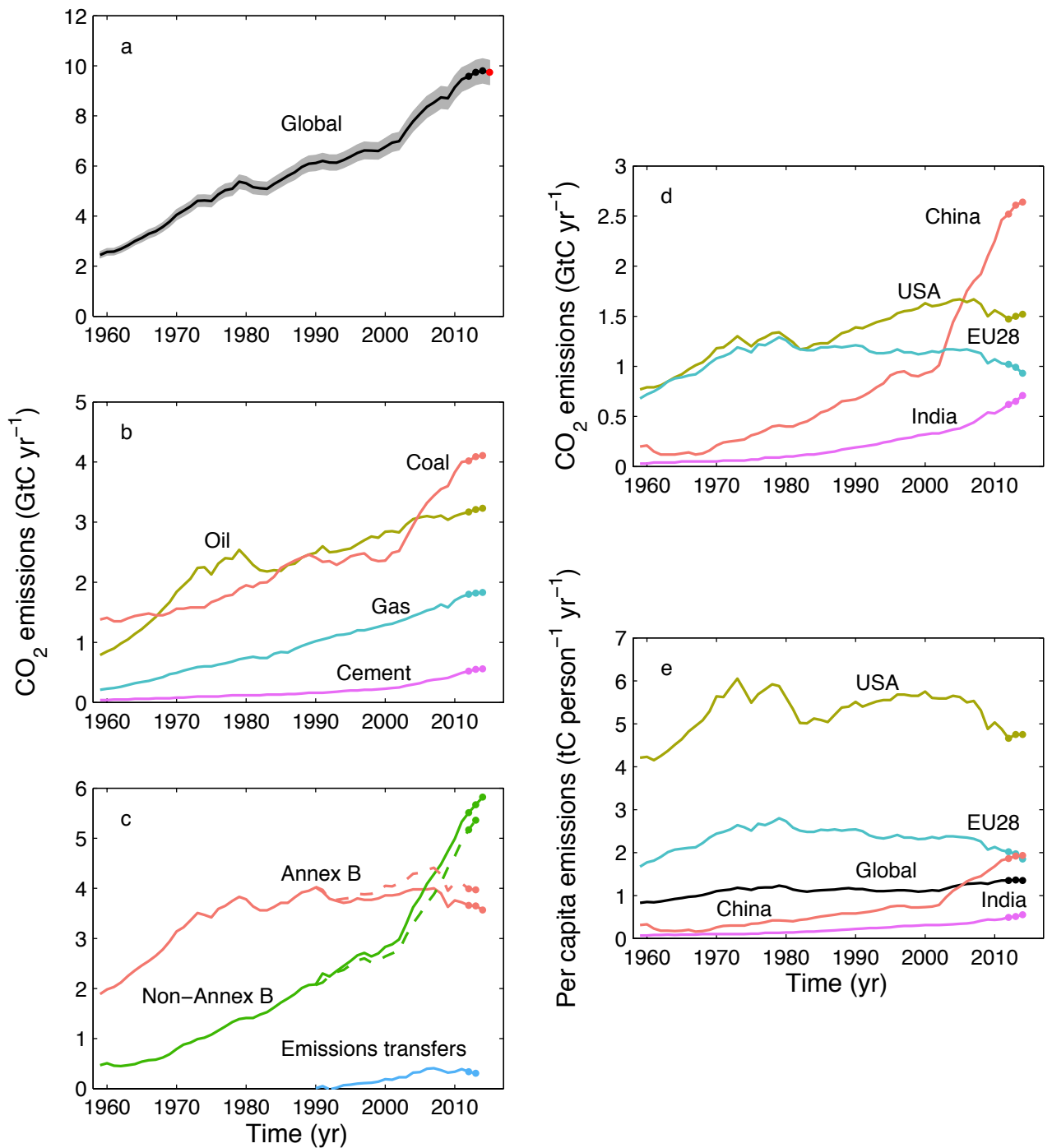
2
3 **Figure 4.** Components of the global carbon budget and their uncertainties as a function of time,
4 presented individually for (a) emissions from fossil fuels and industry (E_{FF}), (b) emissions from
5 land-use change (E_{LUC}), (c) atmospheric CO₂ growth rate (G_{ATM}), (d) the ocean CO₂ sink (S_{OCEAN} ,
6 positive indicates a flux from the atmosphere to the ocean), and (e) the land CO₂ sink (S_{LAND} ,
7 positive indicates a flux from the atmosphere to the land). All time-series are in GtC yr⁻¹ with the
8 uncertainty bounds representing $\pm 1\sigma$ in shaded colour. Data sources are as in Fig. 3. The black

- 1 dots in panels (a), (b) and (e) show values for 2012, 2013 and 2014, that originate from a different
- 2 data set to the remainder of the data, as explained in the text.

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1 **Fig. 5**



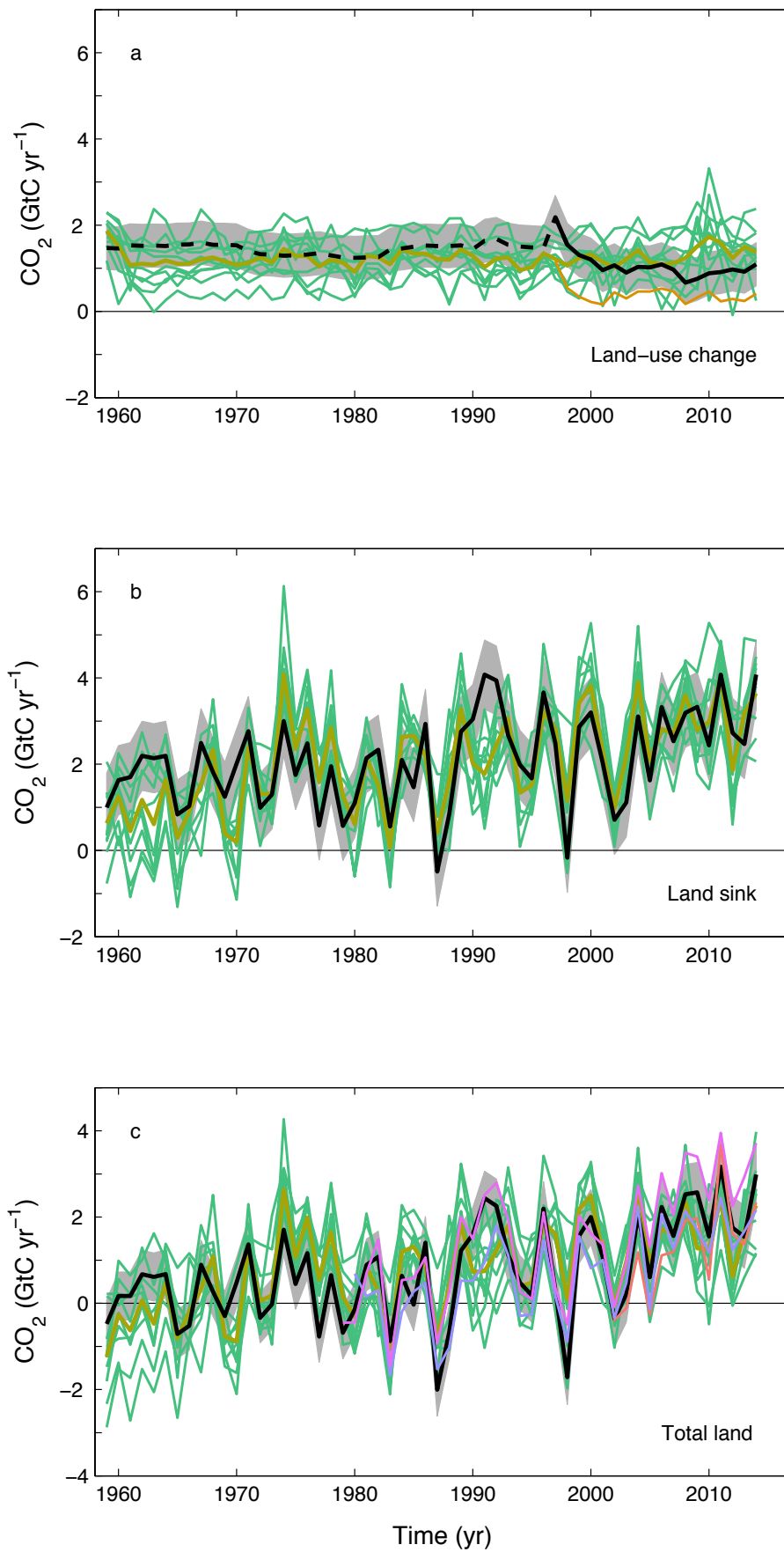
2
 3 **Figure 5.** CO₂ emissions from fossil fuels and industry for (a) the globe, including an uncertainty of
 4 ± 5% (grey shading), the emissions extrapolated using BP energy statistics (black dots) and the
 5 emissions projection for year 2015 based on GDP projection (red dot), (b) global emissions by fuel
 6 type, including coal (salmon), oil (olive), gas (turquoise), and cement (purple), and excluding gas
 7 flaring which is small (0.6% in 2013), (c) territorial (full line) and consumption (dashed line)
 8 emissions for the countries listed in the Annex B of the Kyoto Protocol (salmon lines; mostly

1 advanced economies with emissions limitations) versus non-Annex B countries (green lines), also
2 shown are the emissions transfer from non-Annex B to Annex B countries (light blue line) **(d)**
3 territorial CO₂ emissions for the top three country emitters (USA - olive; China - salmon; India -
4 purple) and for the European Union (EU; turquoise for the 28 member states of the EU in 2012),
5 and **(e)** per-capita emissions for the top three country emitters and the EU (all colours as in panel
6 **(d)**) and the world (black). In panels **(b)** to **(e)**, the dots show the data that were extrapolated from
7 BP energy statistics for 2012, 2013 and 2014. All time-series are in GtC yr⁻¹ except the per-capita
8 emissions (panel **(e)**), which are in tonnes of carbon per person per year (tC person⁻¹ yr⁻¹). All
9 territorial emissions are primarily from Boden et al. (2013) **except national data for the USA and**
10 **EU28 for 1990-2011, which are reported by the countries to the UNFCCC as detailed in the text;**
11 consumption-based emissions are updated from Peters et al. (2011a).

12

13

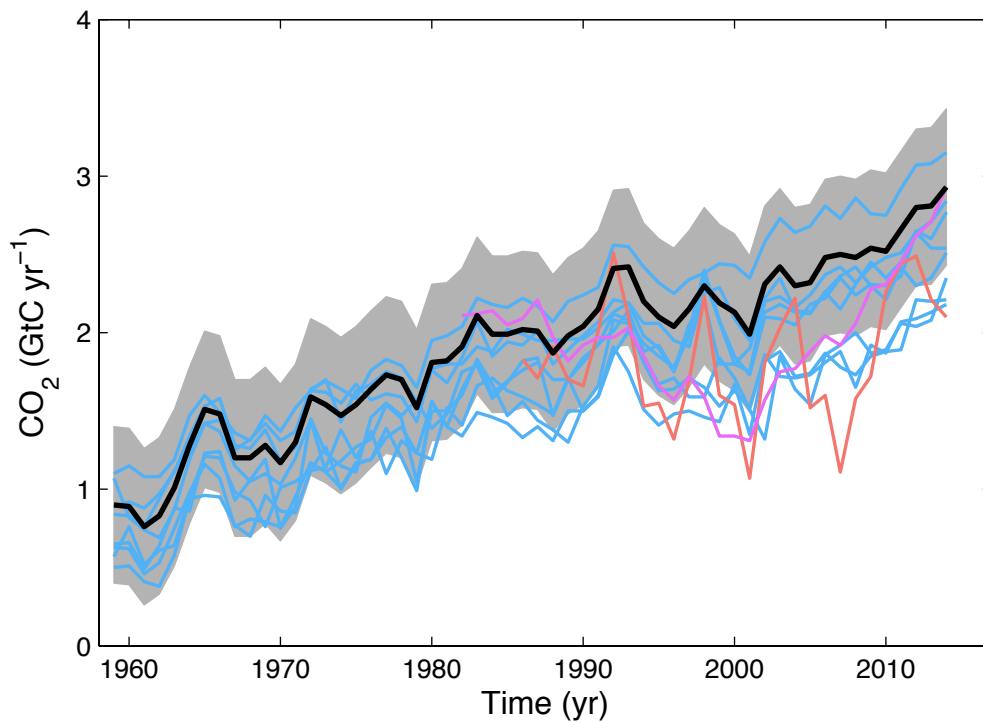
1 **Fig. 6**



2

1 **Figure 6.** Comparison of the atmosphere-land CO₂ flux showing budget values of E_{LUC} (black). (a)
2 CO₂ emissions from land-use change showing individual DGVM model results (green) and the
3 multi model mean (olive), and fire-based results (orange); land-use change data prior to 1997
4 (dashed black) highlights the start of satellite data from that year. (b) Land CO₂ sink (S_{LAND}; black)
5 showing individual DGVM model results (green) and multi model mean (olive). (c) Total land CO₂
6 fluxes (b – a) from DGVM model results (green) and the multi model mean (olive), atmospheric
7 inversions Chevallier et al. (2005; MACC, v14.2) in purple; Rödenbeck et al. (2003; Jena
8 CarboScope, s81_v3.7) in violet; Peters et al. (2010; Carbon Tracker, vCTE2015) in salmon; see
9 Table 6, and the carbon balance from Eq. (1) (black). In (c) the inversions were corrected for the
10 pre-industrial land sink of CO₂ from river input, by adding a sink of 0.45 GtC yr⁻¹ (Jacobson et al.,
11 2007). This correction does not take into account the anthropogenic contribution to river fluxes
12 (see Sect. 2.7.2).

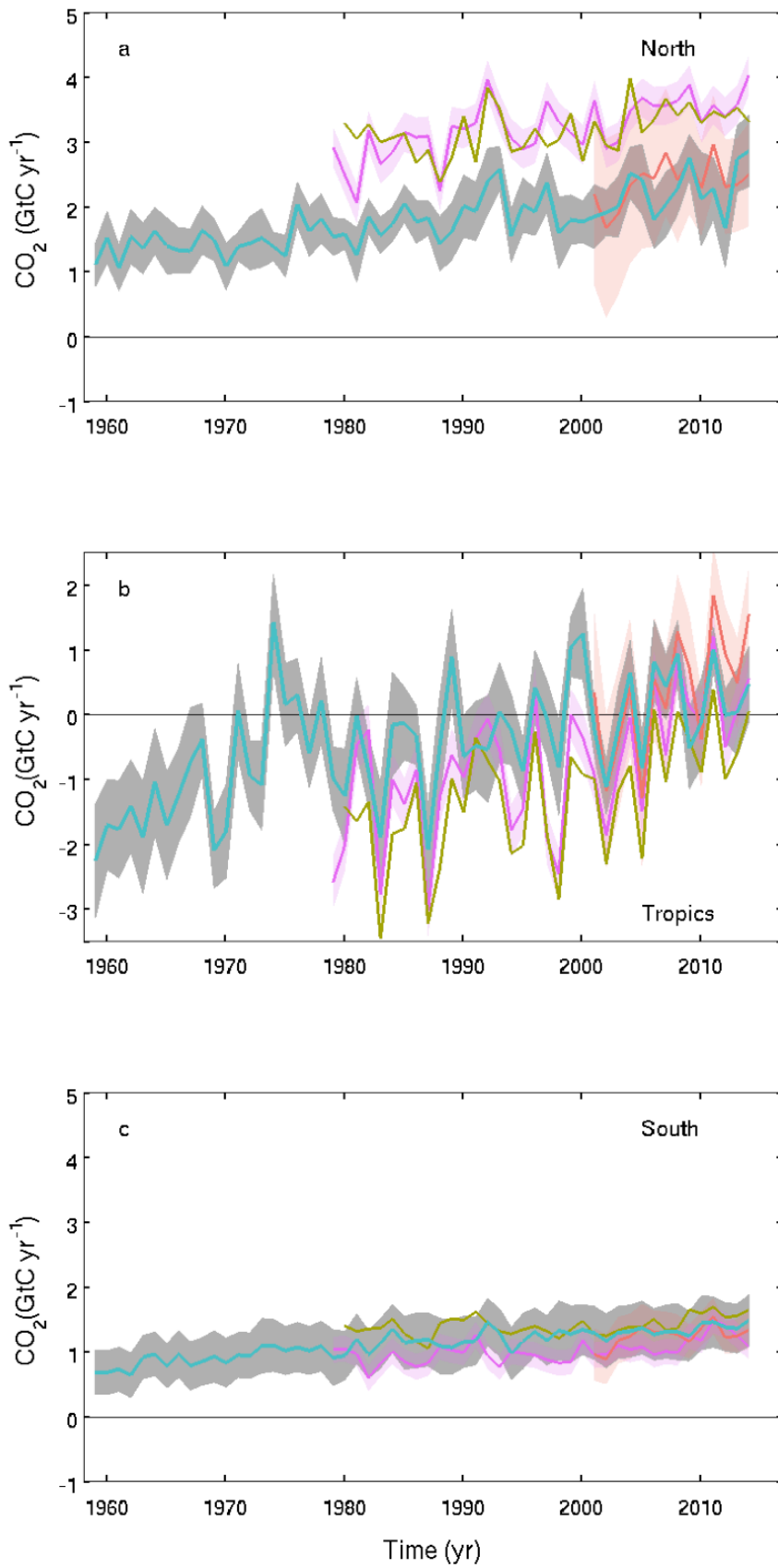
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1 **Fig. 7**

2
 3 **Figure 7.** Comparison of the anthropogenic atmosphere-ocean CO₂ flux shows the budget values
 4 of S_{OCEAN} (black), individual ocean models before normalisation (blue), and the two ocean data-
 5 based products (Rödenbeck et al. (2014) in salmon and Landschützer et al. (2015) in purple; see
 6 Table 6). Both data-based products were adjusted for the pre-industrial ocean source of CO₂ from
 7 river input to the ocean, which is not present in the models, by adding a sink of 0.45 GtC yr⁻¹
 8 (Jacobson et al., 2007), to make them comparable to S_{OCEAN}. This adjustment does not take into
 9 account the anthropogenic contribution to river fluxes (see Section 2.7.2).

10
 11

1 **Fig. 8**



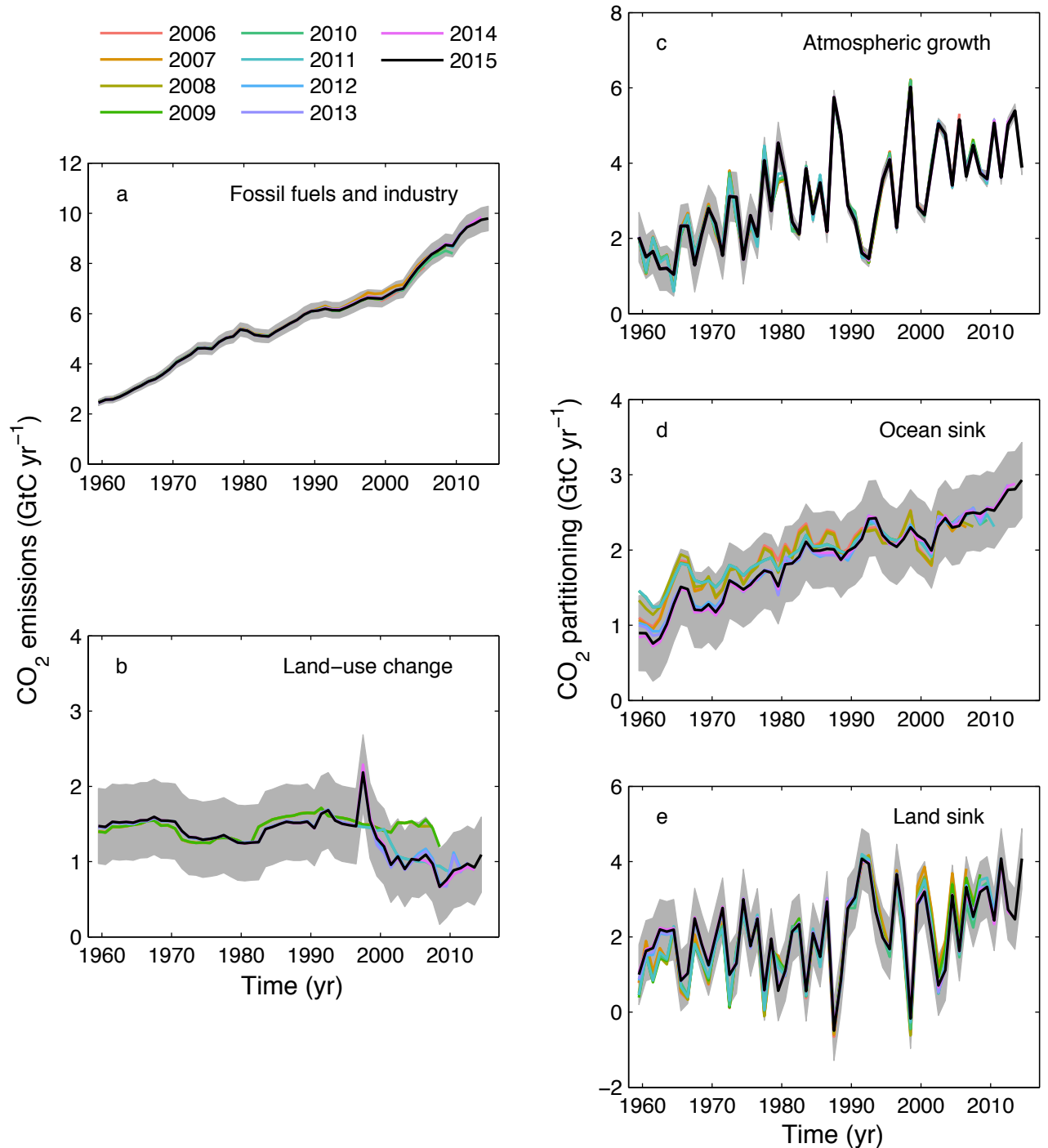
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1 | **Figure 8.** Atmosphere-to-surface CO₂ flux ($S_{\text{OCEAN}} + S_{\text{LAND}} + E_{\text{LUC}}$) by latitude bands for the **(a)** North
2 | (north of 30°N), **(b)** Tropics (30°S-30°N), and **(c)** South (south of 30°S). Estimates from the
3 | combination of the multi-model means for the land and oceans are shown (turquoise) with $\pm 1\sigma$ of
4 | the model ensemble (in grey). Results from the three atmospheric inversions are shown Chevallier
5 | et al. (2005; MACC, v14.2) in purple; Rödenbeck et al. (2003; Jena CarboScope, s81_v3.7) in olive;
6 | Peters et al. (2010; Carbon Tracker, vCTE2015) in salmon; see Table 6.
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1

2 **Fig. 9**



3

4 **Figure 9.** Comparison of global carbon budget components released annually by GCP since 2006.
 5 CO₂ emissions from both (a) fossil fuels and industry (E_{FF}), and (b) land-use change (E_{LUC}), and their
 6 partitioning among (c) the atmosphere (G_{ATM}), (d) the ocean (S_{OCEAN}), and (e) the land (S_{LAND}). See
 7 legend for the corresponding years, with the 2006 carbon budget from Raupach et al.(2007); 2007
 8 from Canadell et al. (2007); 2008 released online only; 2009 from Le Quéré et al. (2009); 2010

- 1 from Friedlingstein et al. (2010); 2011 from Peters et al. (2012b); 2012 from Le Quéré et al. (2013);
- 2 2013 from Le Quéré et al. (2014), 2014 from Le Quéré et al. (2015) and this year's budget (2015;
- 3 this study). The budget year generally corresponds to the year when the budget was first released.
- 4 All values are in GtC yr⁻¹.

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- 1 **Appendix** Attribution of fCO₂ measurements for years 2013-2014 used in addition to SOCAT v3 (Bakker et al., 2014; Bakker et al., in prep.) to
- 2 inform ocean data products.

Vessel	Start date	End date	Regions	No. of samples	Principal Investigators	DOI (if available)/comment
Atlantic Companion	2014-02-21	2014-02-26	North Atlantic	2462	Steinhoff, T. , M. Becker and A. Körtzinger	
Atlantic Companion	2014-04-26	2014-05-02	North Atlantic	3036	Steinhoff, T. , M. Becker and A. Körtzinger	
Atlantic Companion	2014-05-31	2014-06-04	North Atlantic	2365	Steinhoff, T. , M. Becker and A. Körtzinger	
Atlantic Companion	2014-06-16	2014-06-22	North Atlantic	6124	Steinhoff, T. , M. Becker and A. Körtzinger	
Atlantic Companion	2014-08-27	2014-08-30	North Atlantic	3963	Steinhoff, T. , M. Becker and A. Körtzinger	
Atlantic Companion	2014-09-28	2014-10-04	North Atlantic	7239	Steinhoff, T. , M. Becker and A. Körtzinger	
Benguela Stream	2014-07-15	2014-07-20	North Atlantic	4523	Schuster, U.	
Benguela Stream	2013-12-28	2014-01-05	North Atlantic, Tropical Atlantic	6241	Schuster, U.	
Benguela Stream	2014-01-08	2014-01-13	North Atlantic, Tropical Atlantic	4400	Schuster, U.	
Benguela Stream	2014-02-23	2014-03-02	North Atlantic, Tropical Atlantic	6014	Schuster, U.	
Benguela Stream	2014-02-23	2014-03-02	North Atlantic, Tropical Atlantic	5612	Schuster, U.	
Benguela Stream	2014-04-18	2014-04-27	North Atlantic, Tropical Atlantic	7376	Schuster, U.	
Benguela Stream	2014-04-30	2014-05-08	North Atlantic, Tropical Atlantic	6819	Schuster, U.	
Benguela Stream	2014-05-17	2014-05-25	North Atlantic, Tropical Atlantic	6390	Schuster, U.	
Benguela Stream	2014-06-14	2014-06-21	North Atlantic, Tropical Atlantic	3397	Schuster, U.	
Benguela Stream	2014-06-25	2014-07-03	North Atlantic, Tropical Atlantic	6624	Schuster, U.	
Benguela Stream	2014-07-23	2014-07-31	North Atlantic, Tropical Atlantic	6952	Schuster, U.	
Benguela Stream	2014-11-12	2014-11-20	North Atlantic, Tropical Atlantic	5043	Schuster, U.	
Benguela Stream	2014-12-10	2014-12-19	North Atlantic, Tropical Atlantic	7046	Schuster, U.	
Benguela Stream	2014-12-10	2014-12-19	North Atlantic, Tropical Atlantic	7046	Schuster, U.	
Cap Blanche	2014-02-01	2014-02-13	Tropical Pacific, Southern Ocean	6148	Feely, R. , C. Cosca, S. Alin and G. Lebon	
Cap Blanche	2014-03-27	2014-04-10	Tropical Pacific, Southern Ocean	6428	Feely, R. , C. Cosca, S. Alin and G. Lebon	
Cap Blanche	2014-05-23	2014-06-05	Tropical Pacific, Southern Ocean	6016	Feely, R. , C. Cosca, S. Alin and G. Lebon	
Cap Blanche	2014-07-18	2014-07-30	Tropical Pacific, Southern Ocean	5394	Feely, R. , C. Cosca, S. Alin and G. Lebon	
Cap Blanche	2014-09-12	2014-09-25	Tropical Pacific, Southern Ocean	6083	Feely, R. , C. Cosca, S. Alin and G. Lebon	
Cap Blanche	2014-11-13	2014-11-26	Tropical Pacific, Southern Ocean	5876	Feely, R. , C. Cosca, S. Alin and G. Lebon	
Cap Vilano	2013-02-01	2013-02-13	Tropical Pacific, Southern Ocean	4709	Cosca, C., R. Feely , S. Alin and G. Lebon	

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Cap Vilano	2013-03-28	2013-04-11	Tropical Pacific, Southern Ocean	5390	Cosca, C., R. Feely , S. Alin and G. Lebon	
Cap Vilano	2013-05-24	2013-06-06	Tropical Pacific, Southern Ocean	5096	Cosca, C., R. Feely , S. Alin and G. Lebon	
Colibri	2014-07-04	2014-07-15	North Atlantic, Tropical Atlantic	4853	Lefèvre, N. and D. Diverrès	
Colibri	2014-08-27	2014-09-03	North Atlantic, Tropical Atlantic	3881	Lefèvre, N. , and D. Diverrès	
Colibri	2014-09-12	2014-09-23	North Atlantic, Tropical Atlantic	5940	Lefèvre, N. , and D. Diverrès	
Colibri	2014-10-25	2014-11-04	North Atlantic, Tropical Atlantic	5725	Lefèvre, N. and D. Diverrès	
Colibri	2014-07-18	2014-07-19	Tropical Atlantic	313	Lefèvre, N. and D. Diverrès	
Explorer of the Seas	2013-06-25	2013-06-27	North Atlantic	672	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2013-07-06	2013-07-11	North Atlantic	1496	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2013-07-20	2013-07-25	North Atlantic	1375	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2013-08-03	2013-08-08	North Atlantic	1436	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2013-08-17	2013-08-22	North Atlantic	1138	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-04-08	2014-04-09	North Atlantic	209	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-04-19	2014-04-24	North Atlantic	1424	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-05-03	2014-05-08	North Atlantic	1512	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-05-17	2014-05-22	North Atlantic	1349	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-05-31	2014-06-05	North Atlantic	1194	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-06-14	2014-06-19	North Atlantic	1142	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-06-28	2014-07-03	North Atlantic	1479	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-07-12	2014-07-17	North Atlantic	1489	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-07-26	2014-07-31	North Atlantic	1474	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-08-09	2014-08-14	North Atlantic	1468	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-08-23	2014-08-28	North Atlantic	1277	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-08-29	2014-09-06	North Atlantic	2846	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-09-06	2014-09-11	North Atlantic	1479	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-09-11	2014-09-20	North Atlantic	2956	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-09-20	2014-09-22	North Atlantic	728	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-10-04	2014-10-09	North Atlantic	1444	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-10-18	2014-10-23	North Atlantic	1504	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2013-04-02	2013-04-07	North Atlantic, Tropical Atlantic	1301	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2013-06-27	2013-07-06	North Atlantic, Tropical Atlantic	3329	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014

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Explorer of the Seas	2013-07-11	2013-07-20	North Atlantic, Tropical Atlantic	3372	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2013-07-25	2013-08-03	North Atlantic, Tropical Atlantic	3350	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2013-08-08	2013-08-17	North Atlantic, Tropical Atlantic	3393	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-04-01	2014-04-05	North Atlantic, Tropical Atlantic	1189	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-04-10	2014-04-19	North Atlantic, Tropical Atlantic	3297	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-04-24	2014-05-03	North Atlantic, Tropical Atlantic	2968	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-05-08	2014-05-17	North Atlantic, Tropical Atlantic	3324	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-05-22	2014-05-31	North Atlantic, Tropical Atlantic	2850	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-06-05	2014-06-14	North Atlantic, Tropical Atlantic	3374	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-06-19	2014-06-28	North Atlantic, Tropical Atlantic	3386	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-07-03	2014-07-12	North Atlantic, Tropical Atlantic	3397	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-07-17	2014-07-26	North Atlantic, Tropical Atlantic	3404	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-07-31	2014-08-09	North Atlantic, Tropical Atlantic	3392	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-08-14	2014-08-23	North Atlantic, Tropical Atlantic	3307	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-09-25	2014-10-04	North Atlantic, Tropical Atlantic	2967	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-10-09	2014-10-18	North Atlantic, Tropical Atlantic	3069	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-10-23	2014-11-01	North Atlantic, Tropical Atlantic	3074	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-11-01	2014-11-11	North Atlantic, Tropical Atlantic	1809	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-11-21	2014-11-24	North Atlantic, Tropical Atlantic	567	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-12-04	2014-12-13	North Atlantic, Tropical Atlantic	3773	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-12-23	2014-12-27	North Atlantic, Tropical Atlantic	1516	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-12-27	2015-01-04	North Atlantic, Tropical Atlantic	1315	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-11-25	2014-11-29	Tropical Atlantic	1653	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-11-29	2014-12-04	Tropical Atlantic	1680	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-12-14	2014-12-18	Tropical Atlantic	899	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Explorer of the Seas	2014-12-18	2014-12-23	Tropical Atlantic	1787	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_EXP2014
Finnmaid	2012-01-13	2014-12-31	North Atlantic	22000	Glockzin, M.	
G.O. Sars	2014-07-08	2014-11-16	Arctic, North Atlantic	24405	Lauvset, S.K. and I. Skjelvan	
Gordon Gunter	2014-02-20	2014-02-26	North Atlantic	22000	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Gordon Gunter	2014-03-01	2014-03-09	North Atlantic	3742	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Gordon Gunter	2014-03-11	2014-04-03	North Atlantic	8189	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014

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Gordon Gunter	2014-04-08	2014-04-28	North Atlantic	7753	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Gordon Gunter	2014-06-06	2014-06-13	North Atlantic, Tropical Atlantic	3338	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Gordon Gunter	2014-07-04	2014-07-16	Tropical Atlantic	5399	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Gordon Gunter	2014-07-21	2014-07-30	Tropical Atlantic	4074	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-03-29	2014-04-04	North Atlantic	2196	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-04-11	2014-04-25	North Atlantic	6651	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-05-06	2014-05-16	North Atlantic	4302	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-05-16	2014-05-23	North Atlantic	3233	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-05-27	2014-06-01	North Atlantic	2085	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-06-18	2014-07-01	North Atlantic	5458	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-07-25	2014-07-30	North Atlantic	2226	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-08-05	2014-08-16	North Atlantic	5231	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-09-08	2014-09-19	North Atlantic	4847	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-09-23	2014-10-03	North Atlantic	4620	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-10-07	2014-10-23	North Atlantic	7736	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
Henry B. Bigelow	2014-10-28	2014-11-13	North Atlantic	6615	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.AOML_BIGELOW_ECOAST_2014
James Clark Ross	2014-03-20	2014-04-12	North Atlantic	2113	Kitidis, V. and I. Brown	
Laurence M. Gould	2012-12-31	2013-02-06	Southern Ocean	10816	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-02-13	2013-02-24	Southern Ocean	2030	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-03-11	2013-04-07	Southern Ocean	4110	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-04-13	2013-05-05	Southern Ocean	4099	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-05-12	2013-05-24	Southern Ocean	3171	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-06-01	2013-07-05	Southern Ocean	3808	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-09-14	2013-09-26	Southern Ocean	3410	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-10-05	2013-10-22	Southern Ocean	2284	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-10-28	2013-11-15	Southern Ocean	3788	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2013-11-23	2013-12-19	Southern Ocean	7535	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	accessed from CDIAC on 08/06/2015
Laurence M. Gould	2014-01-01	2014-02-07	Southern Ocean	11783	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	
Laurence M. Gould	2014-02-14	2014-03-16	Southern Ocean	5805	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	
Laurence M. Gould	2014-03-22	2014-04-03	Southern Ocean	1109	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	
Laurence M. Gould	2014-04-09	2014-05-10	Southern Ocean	3170	Sweeney, C., T. Takahashi, T. Newberger and D.R. Munro	

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Laurence M. Gould	2014-06-23	2014-08-21	Southern Ocean	3615	Sweeney, C., T. Takahashi, T. Newberger and <u>D.R. Munro</u>	
Laurence M. Gould	2014-09-14	2014-09-26	Southern Ocean	2058	Sweeney, C., T. Takahashi, T. Newberger and <u>D.R. Munro</u>	
Laurence M. Gould	2014-10-08	2014-10-20	Southern Ocean	1642	Sweeney, C., T. Takahashi, T. Newberger and <u>D.R. Munro</u>	
Laurence M. Gould	2014-10-28	2014-11-22	Southern Ocean	6921	Sweeney, C., T. Takahashi, T. Newberger and <u>D.R. Munro</u>	
Laurence M. Gould	2014-11-28	2014-12-20	Southern Ocean	6476	Sweeney, C., T. Takahashi, T. Newberger and <u>D.R. Munro</u>	
Marion Dufresne	2014-01-09	2014-02-16	Indian Ocean, Southern Ocean	7524	Metzl, N. and <u>C. Lo Monaco</u>	
Mirai	2012-11-28	2013-02-13	Southern Ocean	4832	<u>Murata, A.</u>	
Mooring	2012-08-22	2013-07-09	North Atlantic	1507	<u>Sutton, A.</u>	10.3334/CDIAC/OTG.TSM_NH_70W_43N
Mooring	2013-10-04	2014-04-29	North Pacific	1651	<u>Sutton, A.</u>	10.3334/CDIAC/otg.TSM_LaPush_125W_48N
Mooring	2012-11-02	2013-06-06	Tropical Pacific	1257	<u>Sutton, A.</u>	
Mooring	2013-06-06	2013-11-28	Tropical Pacific	1415	<u>Sutton, A.</u>	
New Century 2	2014-08-11	2014-09-08	North Atlantic, Tropical Atlantic, North Pacific, Tropical Pacific	2698	<u>Nakaoka, S.</u>	
New Century 2	2014-12-12	2015-01-12	North Atlantic, Tropical Atlantic, North Pacific, Tropical Pacific	1811	<u>Nakaoka, S.</u>	
New Century 2	2014-04-11	2014-04-26	North Pacific	1608	<u>Nakaoka, S.</u>	
New Century 2	2014-04-27	2014-05-10	North Pacific	1442	<u>Nakaoka, S.</u>	
New Century 2	2014-05-13	2014-05-27	North Pacific	1408	<u>Nakaoka, S.</u>	
New Century 2	2014-05-28	2014-06-09	North Pacific	1392	<u>Nakaoka, S.</u>	
New Century 2	2014-06-12	2014-06-25	North Pacific	1220	<u>Nakaoka, S.</u>	
New Century 2	2014-06-25	2014-07-05	North Pacific	1174	<u>Nakaoka, S.</u>	
New Century 2	2014-09-10	2014-09-24	North Pacific	1108	<u>Nakaoka, S.</u>	
New Century 2	2014-09-25	2014-10-07	North Pacific	1004	<u>Nakaoka, S.</u>	
New Century 2	2014-10-11	2014-10-27	North Pacific	1001	<u>Nakaoka, S.</u>	
New Century 2	2014-10-28	2014-11-09	North Pacific	1174	<u>Nakaoka, S.</u>	
New Century 2	2014-07-14	2014-08-10	North Pacific, Tropical Pacific	2167	<u>Nakaoka, S.</u>	
New Century 2	2014-11-14	2014-12-12	North Pacific, Tropical Pacific	2391	<u>Nakaoka, S.</u>	
Nuka Arctica	2014-07-07	2014-07-15	Arctic, North Atlantic	2333	Omar, A., <u>A. Olsen</u> and T. Johannessen	
Nuka Arctica	2014-08-27	2014-09-05	Arctic, North Atlantic	2607	Omar, A., <u>A. Olsen</u> and T. Johannessen	
Nuka Arctica	2014-09-08	2014-09-18	Arctic, North Atlantic	2398	Omar, A., <u>A. Olsen</u> and T. Johannessen	
Nuka Arctica	2014-01-06	2014-01-12	Arctic, North Atlantic	2369	Omar, A., <u>A. Olsen</u> and T. Johannessen	
Nuka Arctica	2014-01-14	2014-01-24	Arctic, North Atlantic	2728	Omar, A., <u>A. Olsen</u> and T. Johannessen	
Nuka Arctica	2014-01-24	2014-02-01	Arctic, North Atlantic	1990	Omar, A., <u>A. Olsen</u> and T. Johannessen	

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Nuka Arctica	2014-02-04	2014-02-14	Arctic, North Atlantic	2661	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-02-15	2014-02-22	Arctic, North Atlantic	2030	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-02-26	2014-03-05	Arctic, North Atlantic	2179	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-03-07	2014-03-13	Arctic, North Atlantic	2311	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-03-18	2014-03-27	Arctic, North Atlantic	3262	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-03-29	2014-04-05	Arctic, North Atlantic	2799	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-04-09	2014-04-17	Arctic, North Atlantic	3136	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-04-18	2014-04-25	Arctic, North Atlantic	2429	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-05-13	2014-05-18	Arctic, North Atlantic	1420	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-05-23	2014-05-31	Arctic, North Atlantic	1191	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-06-11	2014-06-12	Arctic, North Atlantic	274	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-06-13	2014-06-22	Arctic, North Atlantic	3077	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-07-26	2014-08-05	Arctic, North Atlantic	3362	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-08-08	2014-08-14	Arctic, North Atlantic	2266	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-08-15	2014-08-23	Arctic, North Atlantic	2483	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-09-20	2014-09-28	Arctic, North Atlantic	1931	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-09-28	2014-10-06	Arctic, North Atlantic	769	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-10-08	2014-10-16	Arctic, North Atlantic	1029	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-10-17	2014-10-24	Arctic, North Atlantic	1540	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-10-28	2014-11-06	Arctic, North Atlantic	648	Omar, A., A. Olsen and T. Johannessen
Nuka Arctica	2014-11-20	2014-11-28	Arctic, North Atlantic	1451	Omar, A., A. Olsen and T. Johannessen
Polarstern	2014-07-07	2014-08-02	Arctic	25088	van Heuven, S. and M. Hoppema
Polarstern	2014-08-05	2014-10-04	Arctic	55349	van Heuven, S. and M. Hoppema
Polarstern	2014-06-08	2014-06-30	Arctic, North Atlantic	20871	van Heuven, S. and M. Hoppema
Polarstern	2014-03-09	2014-04-12	North Atlantic, Tropical Atlantic, Southern Ocean	32939	van Heuven, S. and M. Hoppema
Polarstern	2014-10-26	2014-11-28	North Atlantic, Tropical Atlantic, Southern Ocean	30655	van Heuven, S. and M. Hoppema
Polarstern	2013-12-21	2014-03-04	Southern Ocean	69740	van Heuven, S. and M. Hoppema
Polarstern	2014-12-03	2015-01-31	Southern Ocean	28299	van Heuven, S. and M. Hoppema
Pourquoi Pas?	2014-05-17	2014-06-28	North Atlantic	2835	Padin, X.A. and F.F. Pérez
Reykjafoss	2013-09-06	2013-09-17	North Atlantic	3481	Wanninkhof, R., D. Pierrot and L. Barbero
Reykjafoss	2013-09-19	2013-09-30	North Atlantic	3991	Wanninkhof, R., D. Pierrot and L. Barbero

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Reykjafoss	2013-10-17	2013-10-25	North Atlantic	2291	Wanninkhof, R., D. Pierrot and L. Barbero	
Reykjafoss	2013-10-31	2013-11-08	North Atlantic	2715	Wanninkhof, R., D. Pierrot and L. Barbero	
Ronald H. Brown	2013-10-20	2013-10-30	Tropical Atlantic	4608	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_RB_2013
Ronald H. Brown	2014-02-28	2014-03-13	Tropical Pacific	6052	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_RB_2014
Santa Cruz	2014-01-17	2014-01-30	North Atlantic, Tropical Atlantic	5258	Lefèvre, N. and D. Diverres	
Santa Cruz	2014-02-19	2014-02-28	North Atlantic, Tropical Atlantic	3251	Lefèvre, N. and D. Diverres	
Simon Stevin	2014-08-20	2014-08-20	North Atlantic	31827	Gkritzalis, T.	
Simon Stevin	2014-08-21	2014-08-21	North Atlantic	30640	Gkritzalis, T.	
Simon Stevin	2014-08-22	2014-08-22	North Atlantic	5382	Gkritzalis, T.	
Simon Stevin	2014-08-25	2014-08-25	North Atlantic	508	Gkritzalis, T.	
Simon Stevin	2014-08-27	2014-08-27	North Atlantic	28904	Gkritzalis, T.	
Simon Stevin	2014-08-28	2014-08-28	North Atlantic	15148	Gkritzalis, T.	
Simon Stevin	2014-08-29	2014-08-29	North Atlantic	12492	Gkritzalis, T.	
Simon Stevin	2014-09-01	2014-09-01	North Atlantic	21372	Gkritzalis, T.	
Simon Stevin	2014-09-03	2014-09-03	North Atlantic	23069	Gkritzalis, T.	
Simon Stevin	2014-09-08	2014-09-08	North Atlantic	24445	Gkritzalis, T.	
Simon Stevin	2014-10-22	2014-10-23	North Atlantic	28397	Gkritzalis, T.	
Simon Stevin	2014-10-24	2014-10-24	North Atlantic	11920	Gkritzalis, T.	
Skogafoss	2014-03-17	2014-04-11	North Atlantic	10168	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_SKO2014
Skogafoss	2014-05-10	2014-06-05	North Atlantic	11010	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_SKO2014
Skogafoss	2014-06-07	2014-06-28	North Atlantic	6702	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_SKO2014
Skogafoss	2014-06-29	2014-07-26	North Atlantic	7280	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_SKO2014
Skogafoss	2014-07-27	2014-08-21	North Atlantic	5528	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_SKO2014
Skogafoss	2014-08-22	2014-09-01	North Atlantic	3601	Wanninkhof, R., D. Pierrot and L. Barbero	10.3334/CDIAC/OTG.VOS_SKO2014
Soyo-maru	2013-12-08	2013-12-19	North Pacific	10583	Ichikawa, T. and T. Ono	
Soyo-maru	2014-02-10	2014-02-24	North Pacific	15841	Ichikawa, T. and T. Ono	
Soyo-maru	2014-03-02	2014-03-09	North Pacific	9589	Ichikawa, T. and T. Ono	
Soyo-maru	2014-05-10	2014-05-18	North Pacific	9608	Ichikawa, T. and T. Ono	
Soyo-maru	2014-05-24	2014-06-19	North Pacific	29872	Ichikawa, T. and T. Ono	
Soyo-maru	2014-08-22	2014-08-26	North Pacific	4162	Ichikawa, T. and T. Ono	
Soyo-maru	2014-01-24	2014-01-30	North Pacific, Tropical Pacific	8784	Ichikawa, T. and T. Ono	

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Trans Future 5	2013-08-26	2013-08-27	North Pacific	58	Nakaoka, S. and Y. Nojiri
Trans Future 5	2013-09-27	2013-09-27	North Pacific	63	Nakaoka, S. and Y. Nojiri
Trans Future 5	2013-11-04	2013-11-05	North Pacific	58	Nakaoka, S. and Y. Nojiri
Trans Future 5	2013-11-08	2013-11-09	North Pacific	52	Nakaoka, S. and Y. Nojiri
Trans Future 5	2013-12-16	2013-12-16	North Pacific	56	Nakaoka, S. and Y. Nojiri
Trans Future 5	2013-12-20	2013-12-20	North Pacific	56	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-02-10	2014-02-10	North Pacific	77	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-02-14	2014-02-15	North Pacific	41	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-03-24	2014-03-25	North Pacific	63	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-03-28	2014-03-29	North Pacific	61	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-05-06	2014-05-07	North Pacific	73	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-05-09	2014-05-09	North Pacific	59	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-06-16	2014-06-17	North Pacific	70	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-06-20	2014-06-20	North Pacific	61	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-07-28	2014-07-29	North Pacific	71	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-08-01	2014-08-01	North Pacific	50	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-09-08	2014-09-08	North Pacific	55	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-09-12	2014-09-12	North Pacific	54	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-10-20	2014-10-21	North Pacific	53	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-10-24	2014-10-24	North Pacific	55	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-12-01	2014-12-01	North Pacific	52	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-12-05	2014-12-05	North Pacific	53	Nakaoka, S. and Y. Nojiri
Trans Future 5	2013-09-28	2013-10-09	North Pacific, Tropical Pacific	1118	Nakaoka, S. and Y. Nojiri
Trans Future 5	2013-11-09	2013-11-18	North Pacific, Tropical Pacific	1104	Nakaoka, S. and Y. Nojiri
Trans Future 5	2013-12-21	2014-01-02	North Pacific, Tropical Pacific	1168	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-02-16	2014-02-25	North Pacific, Tropical Pacific	1122	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-03-30	2014-04-09	North Pacific, Tropical Pacific	1121	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-05-10	2014-05-19	North Pacific, Tropical Pacific	1159	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-06-21	2014-07-02	North Pacific, Tropical Pacific	1124	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-08-02	2014-08-11	North Pacific, Tropical Pacific	1142	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-10-25	2014-11-04	North Pacific, Tropical Pacific	1086	Nakaoka, S. and Y. Nojiri

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Trans Future 5	2014-12-06	2014-12-15	North Pacific, Tropical Pacific	1104	Nakaoka, S. and Y. Nojiri
Trans Future 5	2013-10-23	2013-11-03	North Pacific, Tropical Pacific, Southern Ocean	1432	Nakaoka, S. and Y. Nojiri
Trans Future 5	2013-12-03	2013-12-15	North Pacific, Tropical Pacific, Southern Ocean	1434	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-01-25	2014-02-07	North Pacific, Tropical Pacific, Southern Ocean	1558	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-03-12	2014-03-23	North Pacific, Tropical Pacific, Southern Ocean	1451	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-04-24	2014-05-05	North Pacific, Tropical Pacific, Southern Ocean	1381	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-06-03	2014-06-15	North Pacific, Tropical Pacific, Southern Ocean	1456	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-07-16	2014-07-27	North Pacific, Tropical Pacific, Southern Ocean	1415	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-08-27	2014-09-07	North Pacific, Tropical Pacific, Southern Ocean	1405	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-10-06	2014-10-19	North Pacific, Tropical Pacific, Southern Ocean	1422	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-11-18	2014-11-29	North Pacific, Tropical Pacific, Southern Ocean	809	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-09-23	2014-10-05	Southern Ocean	196	Nakaoka, S. and Y. Nojiri
Trans Future 5	2013-10-09	2013-10-21	Tropical Pacific, Southern Ocean	880	Nakaoka, S. and Y. Nojiri
Trans Future 5	2013-11-19	2013-12-01	Tropical Pacific, Southern Ocean	921	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-01-02	2014-01-17	Tropical Pacific, Southern Ocean	1000	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-02-25	2014-03-10	Tropical Pacific, Southern Ocean	909	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-04-10	2014-04-23	Tropical Pacific, Southern Ocean	941	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-05-20	2014-06-01	Tropical Pacific, Southern Ocean	910	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-07-02	2014-07-15	Tropical Pacific, Southern Ocean	1027	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-08-12	2014-08-25	Tropical Pacific, Southern Ocean	1040	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-11-05	2014-11-17	Tropical Pacific, Southern Ocean	853	Nakaoka, S. and Y. Nojiri
Trans Future 5	2014-12-16	2014-12-30	Tropical Pacific, Southern Ocean	939	Nakaoka, S. and Y. Nojiri
Wakataka-maru	2014-05-10	2014-05-20	North Pacific	9360	Kuwata, A. and K. Tadokoro
Wakataka-maru	2014-06-05	2014-06-11	North Pacific	9025	Kuwata, A. and K. Tadokoro
Walton Smith	2013-03-31	2013-04-18	North Atlantic, Tropical Atlantic	8392	Millero, F.
Walton Smith	2013-04-19	2013-04-28	North Atlantic, Tropical Atlantic	4890	Millero, F.
Walton Smith	2014-04-28	2014-05-25	North Atlantic, Tropical Atlantic	12666	Millero, F.
Walton Smith	2013-05-25	2013-05-27	Tropical Atlantic	898	Millero, F.
Walton Smith	2013-06-13	2013-06-15	Tropical Atlantic	1214	Millero, F.
Walton Smith	2013-06-20	2013-06-27	Tropical Atlantic	2883	Millero, F.
Walton Smith	2013-07-06	2013-07-18	Tropical Atlantic	5529	Millero, F.

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Walton Smith	2013-08-13	2013-08-28	Tropical Atlantic	7900	<u>Millero, F.</u>
Walton Smith	2013-10-08	2013-10-09	Tropical Atlantic	509	<u>Millero, F.</u>
Walton Smith	2013-10-17	2013-10-18	Tropical Atlantic	707	<u>Millero, F.</u>
Walton Smith	2013-12-20	2013-12-21	Tropical Atlantic	748	<u>Millero, F.</u>
Walton Smith	2014-04-22	2014-04-22	Tropical Atlantic	214	<u>Millero, F.</u>
Walton Smith	2014-04-23	2014-04-24	Tropical Atlantic	657	<u>Millero, F.</u>
Walton Smith	2014-04-26	2014-04-26	Tropical Atlantic	155	<u>Millero, F.</u>

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