Contributions to accelerating atmospheric CO₂ growth from economic activity, carbon intensity, and efficiency of natural sinks


The growth rate of atmospheric carbon dioxide (CO₂), the largest human contributor to human-induced climate change, is increasing rapidly. Three processes contribute to this rapid increase. Two of these processes concern emissions. Recent growth of the world economy combined with an increase in its carbon intensity have led to rapid growth in fossil fuel CO₂ emissions since 2000: comparing the 1990s with the 2000–2006 period, emissions growth rate increased from 1.3 to 3.3% y⁻¹. The third process is indicated by increasing evidence (P = 0.089) for a long-term (50-year) increase in the airborne fraction (AF) of CO₂ emissions, implying a decline in the efficiency of CO₂ sinks on land and oceans in absorbing anthropogenic emissions. Since 2000, the contributions of these three factors to the increase in the atmospheric CO₂ growth rate have been 65 ± 16% from increasing global economic activity, 17 ± 6% from the increasing carbon intensity of the global economy, and 18 ± 15% from the increase in AF. An increasing AF is consistent with results of climate–carbon cycle models, but the magnitude of the observed signal appears larger than that estimated by models. All of these changes characterize a carbon cycle that is generating stronger-than-expected and sooner-than-expected climate forcing.

## Results and Discussion

### Growth in Atmospheric CO₂

Global average atmospheric CO₂ rose from 280 ppm at the start of the industrial revolution (~1750) to 381 ppm in 2006. The present concentration is the highest during the last 650,000 years (5, 6) and probably during the last 20 million years (7). The growth rate of global average atmospheric CO₂ for 2000–2006 was 1.93 ppm y⁻¹ [or 4.1 petagrams of carbon (PgC) y⁻¹, Table 1]. This rate is the highest since the beginning of continuous monitoring in 1959 and is a significant increase over growth rates in earlier decades: the average growth rates for the 1980s and the 1990s were 1.58 and 1.49 ppm y⁻¹, respectively (Fig. 1).

### CO₂ Emissions

From 1850 to 2006, fossil fuel and cement emissions released a cumulative total of ~330 PgC to the atmosphere (1 PgC = 1 petagram or 10¹⁵ metric tons of carbon). An additional 158 PgC came from land-use-change emissions, largely deforestation and wood harvest (see Methods for data sources and uncertainties).

Fossil fuel and cement emissions (F_Foss) increased from 7.0 PgC y⁻¹ in 2000 to 8.4 PgC y⁻¹ in 2006, 35% above emissions in 1990. The average F_Foss for 2000–2006 was 7.6 ± 0.4 PgC y⁻¹ (Table 1). The average proportional growth rate of F_Foss increased from 1.3% y⁻¹ for 1990–1999 to 3.3% y⁻¹ for 2000–2006 (Fig. 1B).

Model-based estimates of emissions from land-use change...
The carbon intensity of the global economy decreased from 0.35 kilograms of carbon (kgC)/dollar in 1970 to 0.24 kgC/dollar in 2000. This decreasing trend stopped after 2000, and since then, the carbon intensity of gross world product (GWP) has increased, reaching 0.27 kgC/dollar in 2006. This increase in carbon intensity was due to the growth of the global economy and the continued increase in CO2 emissions from land-use change.

Changes in the long-term efficiency of the natural sinks in removing atmospheric CO2, as measured by the ratio of sinks to anthropogenic emissions (AF), can be explained by the movements of CO2 between the atmosphere, land, and ocean. The AF has a large interannual variability and has ranged from 0.0 to 0.8 since 1959. This variability is mainly due to the responses of natural sinks, particularly land sinks, to interannual climate variability (e.g., from El Niño/Southern Oscillation) and volcanic eruptions. The AF has increased by 0.21% per year from 1990 to 2006, and the observed mean sink of 2.2 PgC y\(^{-1}\) for the period 1990–2006 was very near the upper limit of the interannual variability (12). We calculated net land exchange (excluding emissions from land-use change) as the residual. On the basis of this partitioning, the ocean sink accounted for 24% of total anthropogenic emissions from 2000 to 2006, and the land sinks accounted for the remaining 30%.

Changes in the long-term efficiency of the natural sinks in removing atmospheric CO2, as measured by the ratio of sinks to anthropogenic emissions, are indicated by the proportional trend in the AF [(1/AF)\(d\text{AF}/dt\)]. Over the period 1959–2006, this was +0.25 ± 0.21% y\(^{-1}\) (mean ± standard deviation of estimate), with significance \(P = 0.89\) for a trend >0 [Table 1 and Fig. 2A; see Methods and supporting information (SI) Text for computational and statistical details]. Although the significance of this trend is lower than the conventional criterion of \(P = 0.95\), the observed AF trend is sufficiently significant to justify reflecting it in the

### Table 1. Summary of means and proportional trends of the global carbon budget for various time periods

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<tbody>
<tr>
<td>Fossil Fuel ((F_{\text{Foss}}))</td>
<td>5.3</td>
<td>5.6</td>
<td>6.5</td>
<td>7.6</td>
<td>2.12</td>
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<tr>
<td>Land Use Change ((F_{\text{LUC}}))</td>
<td>1.5</td>
<td>1.5</td>
<td>1.6</td>
<td>1.5</td>
<td>0.21</td>
</tr>
<tr>
<td>Total ((F_{\text{Foss}} + F_{\text{LUC}}))</td>
<td>6.7</td>
<td>7.0</td>
<td>8.0</td>
<td>9.1</td>
<td>1.71</td>
</tr>
<tr>
<td>Sinks, PgC y(^{-1})</td>
<td>2.9</td>
<td>3.1</td>
<td>3.2</td>
<td>4.1</td>
<td>1.89</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>1.9</td>
<td>2.0</td>
<td>2.2</td>
<td>2.2</td>
<td>1.25</td>
</tr>
<tr>
<td>Ocean</td>
<td>1.9</td>
<td>2.0</td>
<td>2.7</td>
<td>2.8</td>
<td>1.87</td>
</tr>
<tr>
<td>Distribution of annual emissions</td>
<td>0.43</td>
<td>0.44</td>
<td>0.39</td>
<td>0.45</td>
<td>0.25 ± 0.21</td>
</tr>
<tr>
<td>Atmosphere‡</td>
<td>0.28</td>
<td>0.28</td>
<td>0.27</td>
<td>0.24</td>
<td>−0.42</td>
</tr>
<tr>
<td>Land</td>
<td>0.29</td>
<td>0.28</td>
<td>0.34</td>
<td>0.30</td>
<td>0.06</td>
</tr>
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*The proportional trend for a quantity X(t) is \((X)/\text{d}X/\text{d}t\), where angle brackets denote an average over the indicated period.
†Data available from 1970 only.
‡This is the airborne fraction.
§This value (mean ± standard deviation) of the proportional trend in AF was determined from the noise-reduced (monthly) series for AF (see Methods and SI Text). All other proportional trend estimates were derived from the annual series.

The GWP data used throughout this paper are based on market exchange rates (MER). In ref. 3, we show that our main conclusions, particularly the reversal of the trend in Fig. 1A, are evident using either the MER or purchasing power parity definition for GWP.
attributing the recent changes in the growth rate of atmospheric CO₂.

Climate models that include a representation of carbon cycle sinks estimate a proportional trend in the AF during the 21st century of 0.41%/H110060.23%/y1 (mean/standard deviation across 11 models) under a Special Report on Emission Scenarios (SRES) A2 scenario (13). However, over the 1959–2006 time period, 9 of the 11 models estimate a decrease in AF, and the mean proportional trend is 0.27%/0.36%/y1 (11 models). These results suggest that the observed carbon-cycle feedbacks occur faster than expected by our current understanding of the processes driving the sinks.

The increase in the AF implies that carbon emissions have grown faster than CO₂ sinks on the land and oceans. Because the land and oceans are both mosaics of regions that are gaining and regions that are losing carbon, this trend could result from any or all of three scenarios: sink regions could have weakened, either absolutely or relative to growing emissions; source regions could have intensified; or sink regions could have transitioned to sources.

Whereas both land and ocean sinks continue to accumulate carbon on average at ~5.0 ± 0.6 PgC y⁻¹ since 2000, large regional sinks have been weakening. In the Southern Ocean, the poleward displacement and intensification of westerly winds caused by human activities has enhanced the ventilation of carbon-rich waters normally isolated from the atmosphere at least since 1980, and contributed nearly half of the decrease in the ocean CO₂ uptake fraction estimated by the model (Fig. 2C, ref. 11). On land, a number of major droughts in midlatitude regions in 2002–2005 have contributed to the weakening of the growth rate of terrestrial carbon sinks in these regions (14–17).

**Attribution of Factors Driving the Atmospheric CO₂ Growth Rate.** The growth rate of atmospheric CO₂ depends on three classes of factors: global economic activity (generated from the use of fossil fuels and land-use change), the carbon intensity of the economy, and the functioning of unmanaged carbon sources and sinks on land and in oceans. Since 2000, a growing global economy, an increase in the carbon emissions required to produce each unit of economic activity, and a decreasing efficiency of carbon sinks on land and in oceans have combined to produce the most rapid 7-year increase in atmospheric CO₂ since the beginning of continuous atmospheric monitoring in 1959. This is also the most rapid increase since the beginning of the industrial revolution (18).

We estimate that 35 ± 16% of the increase in atmospheric CO₂ growth rate between 1970–1999 and 2000–2006 was caused by the decrease in the efficiency of the land and ocean sinks in removing anthropogenic CO₂ (18 ± 15%) and by the increase in carbon intensity of the global economy (17 ± 6%). The remaining 65 ± 16% was due to the increase in the global economy (see Methods).

Many of the existing scenarios for the 21st century assume continued economic growth (9), although none assume the...
long-term maintenance of the growth rates that have characterized China and India over the last decade. The overwhelming majority of the existing scenarios project sustained decreases in the carbon intensity of the global energy system. The recent acceleration of emissions is a consequence of many factors, including an overall surge in energy demand and production of electricity from coal, increased energy per capita, and population growth (3, 19).

The rapid growth in the atmospheric CO₂ growth rate since 2000 is caused by increasing CO₂ emissions (associated in turn with accelerating global economic growth and an increasing carbon intensity of the global economy) and also an increase in the AF of CO₂ emissions. Together, these effects characterize a carbon cycle that is generating stronger-than-expected climate forcing sooner than expected.

**Methods**

Original data to complete the global carbon budget are generated by multiple agencies and research groups around the world and are collated annually by the Global Carbon Project (www.globalcarbonproject.org). Data are available for the period of 1850–2006 and can be downloaded from www.globalcarbonproject.org/carbonbetrands.

**Atmospheric CO₂ Concentration.** We use monthly and annual-mean atmospheric CO₂ concentration analyzed and compiled by the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory in Colorado (www.esrl.noaa.gov/gmd/ccgg/trends) and published by the Carbon Dioxide Information Analysis Center (CDIAC) along other historical data based on ice core analyses (http://cdiac.ornl.gov/trends/co2/contents.htm). From 1959 to 1980, data came from the Mauna Loa observatory (Hawaii, U.S.) and since 1980 represent a globally averaged CO₂ concentration using weighted observations from many laboratories.

**Carbon Emissions from Fossil Fuel.** Carbon emissions from fossil fuel combustion were based on country-level energy data, plus estimates on the global consumption of coal, oil, and natural gas, by using standard conversions to CO₂ emission (20, 21). Emissions from the calcining of limestone to produce cement add ∼3.8% to global CO₂ emissions. From 1950 to 2004, we used the energy statistics published by the United Nations (U.N.) Department for Economic and Social Information and Policy Analysis (22). Energy statistics are compiled from annual questionnaires distributed by the U.N. Statistical Office and supplemented by official national statistical publications. For the years 2005 and 2006, data from the British Petroleum Statistical Review of World Energy (23) were used. Statistics on cement production are compiled by the U.S. Department of Interior’s Geological Survey. Carbon dioxide emissions from fossil fuels and cement since 1751 are archived and distributed by the CDIAC (24).

**Carbon Emissions from Land-Use Change.** Emissions due to land use change (e.g., harvesting of forest products and clearing for agriculture) include the net flux of carbon between the terrestrial biosphere and the atmosphere resulting from deliberate changes in land cover and land use (25, 26). Global net-carbon fluxes from changes in land use were estimated with a bookkeeping model to track the carbon in living vegetation, dead plant material, wood products, and soils for each hectare of land cultivated, harvested, or reforested. We used the carbon emissions for the period of 1959–2000 (25), calculated the emissions for the period 2000–2005, and revised the estimates for the 1990s (which changed from 2.1 Pg C y⁻¹ to 1.6 Pg C y⁻¹) by using the updated and revised data on land-use change from the U.N. Food and Agriculture Organization Global Forest Resource Assessment (26). Data for 2006 are not available, but it has been assumed to be the same as in the period 1990–2005. Historical data from 1850 are archived and distributed by the CDIAC (27).

**Carbon Intensity of the Global Economy.** The carbon intensity of the global economy is calculated as F_{Foss}/GWP. This measure is the product of the energy consumed per dollar of economic activity (the energy intensity of the economy) and the carbon emitted per unit of energy (the carbon intensity of the energy). The GWP is the total gross national product of all of the countries in the world, i.e., the total world gross domestic product. The data are collected and analyzed by the United Nations Statistics Division. The data are based on market exchange rates expressed in U.S. dollars and referenced to 1990, with inflation removed.

**Trend in AF.** We used three time series to determine the trend in the AF, AF = (dC_{at}/dt)/(F_{Foss} + F_{LUC}), where dC_{at}/dt is the growth rate of atmospheric CO₂ (Pg C y⁻¹). The first “annual” AF series used the annual mean data as described above. The second “monthly” series was constructed from monthly atmospheric CO₂ data, with removal from dC_{at}/dt of the regularly repeating annual cycle in global CO₂ caused mainly by the spring vegetation flush in the Northern Hemisphere. The third “noise-reduced” series was another monthly series in which a filtering method was used to reduce noise by removing the component of dC_{at}/dt correlated with El Nin˜o events and volcanic activity. Methodologies for constructing the second and third series are given in SI Text.

The trend in AF was estimated by fitting a first-order autoregressive (1) model to the monthly AF data as in ref. 12. The statistical significance of the trend was estimated from a 1,000-member Monte Carlo ensemble simulation, which had similar noise properties as the AF data. Finally, the standard deviation of the trends from the 1,000-member simulation was calculated to provide the uncertainty in the result.

The three time series yielded nearly identical proportional trends in AF, with values of 0.24 ± 0.33% y⁻¹ (P = 0.76) for the annual series, 0.24 ± 0.34% y⁻¹ (P = 0.79) for the monthly series, and 0.25 ± 0.21% y⁻¹ (P = 0.89) for the noise-reduced series. The significance of the results increases between the annual and the monthly series because of the larger number of independent data, as well as between the monthly and noise-reduced series because of the removal of natural variability, which does not show any trends. We used the results with the highest significance, those from the noise-reduced data.

**Data Uncertainty.** The uncertainty in the sources and sinks of CO₂ were estimated as follows:

- An uncertainty of 5% was assigned to emissions from fossil fuel and cement, which takes into account errors in the reporting of energy statistics and in the conversion from energy consumption to CO₂ emissions.
- An uncertainty of ±0.5 Pg C y⁻¹ was assigned to land-use change. This uncertainty is revised downwards from previous assessments (28) because our land-use estimates calculated with the revised Food and Agriculture Organization Global Forest Assessment (26) are now consistent with three independent estimates based of satellite data and terrestrial models (29–31). Emissions from land-use change remain as the most uncertain of all quantities required to close the global carbon budget.
- An uncertainty of ±0.04 Pg C y⁻¹ was estimated for the C accumulation in the atmosphere on the basis of the standard deviation of the observations. This uncertainty is low because of the high quality of atmospheric CO₂ measurements and because of the fast-mixing time scale of the atmosphere, which allows for an estimation of a global mean value with relatively few sites.
An uncertainty of $\pm 0.4 \text{PgC yr}^{-1}$ was assigned to the ocean CO$_2$ sink on the basis of the convergence of the estimates for the 1990s by both the model used here and estimates based on oceanic and atmospheric observations (32–34), as in ref. 12.

An uncertainty of $\pm 0.7 \text{PgC yr}^{-1}$ was applied to the land sink from a quadratic sum of the uncertainty in the other components of the CO$_2$ budget. Note that the uncertainty of the land plus ocean sinks ($\pm 0.6 \text{PgC yr}^{-1}$) is smaller than their combined uncertainties because it is based on the quadratic sum of the uncertainties in the emissions and atmospheric CO$_2$ growth rate.

The uncertainty in AF is 9%, which is based on the sum of the uncertainties in $\Delta C_{\text{air}}$ and of the total emissions. The trend in annual AF of 0.25% $y^{-1}$ exceeds the uncertainty in the annual AF after 36 years, for a total time series of 48 years.

**Attribution of Factors Driving the Atmospheric CO$_2$ Growth Rate.** We estimated the impact of the change in trajectory of carbon intensity between 1970–1999 and 2000–2006 by projecting the trend in carbon intensity during 1970–1999 ($-0.0038 \text{kgC/USDollar per year}$) to the later period. The projected carbon intensity of 0.229 kgC/USDollar is lower than the observed value of 0.242 in 2000–2006. The difference of 0.0129 $\pm 0.0045$ kgC/USDollar includes an uncertainty of $\pm 1$ standard deviation estimated from fitting a first-order autoregressive (1) model and computing a 1,000-member simulation, as for the AF, but applied to the departure of the 2000–2006 carbon intensity from the extrapolated trend. The P value of this time series exceeds 0.99. To calculate CO$_2$ emissions, we multiplied this projected intensity of 0.229 kgC/USDollar is lower than the observed 0.242 kgC/USDollar per year) to the later period. The projected carbon intensity between 1970–1999 and 2000–2006 by projecting the trend in annual AF of 0.25% $y^{-1}$.

To estimate the excess atmospheric CO$_2$ growth rate in 2000–2006 ($\pm 0.182 \pm 0.066 \text{PgC yr}^{-1}$), this product of 0.19 $\pm 0.16$ PgC yr$^{-1}$ is the excess CO$_2$ growth rate due to the increase in AF. It corresponds to 18–15% of the increase in atmospheric CO$_2$ growth rate between the two time periods (0.19 PgC yr$^{-1}$)/(1.047 PgC yr$^{-1}$).

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