CLOSING THE GLOBAL BUDGET FOR CO_2

Accurate global knowledge of where carbon is coming from and where it is going is essential to put in place international emissions reductions strategies. **Corinne Le Quéré** explains how the Global Carbon Project is contributing.

Carbon dioxide (CO_2) has been increasing in the atmosphere since the 18th century as a side effect of industrialisation. At first, the main culprit was large-scale deforestation for agricultural conversion. During the 20th century, energy from fossil fuels became widely used and now accounts for over 80 percent of the global CO_2 emissions. All together, 500-550 gigatonnes of carbon (GtC) in the form of CO_2 will have been emitted to the atmosphere before 2010. Yet, the increase of CO_2 in the atmosphere is less than half of the CO_2 emitted. Can we account for the remaining CO_2?

The available scientific knowledge tells us that the two large carbon reservoirs – the terrestrial biosphere and the oceans – have taken up the excess CO_2 in approximately equal proportions. However these CO_2 "sinks" are not fixed, in fact they are highly variable and respond to elevated atmospheric CO_2 levels and changes in the climate. To account fully for all the CO_2 emitted, we need to know the size of the land and ocean CO_2 sinks and their evolution in time. And we need to know this with an accuracy that is higher than the uncertainty in CO_2 emissions themselves. Full accounting of CO_2 emissions is a necessity if we are to monitor the transition from a CO_2-intensive to a low CO_2 economy. Unaccounted CO_2 emissions open the door to all kinds of abuses, from inaccurate accounting and declaration of countries' emissions to misleading demands for carbon credits associated with Clean Development Mechanisms and geoengineering options.

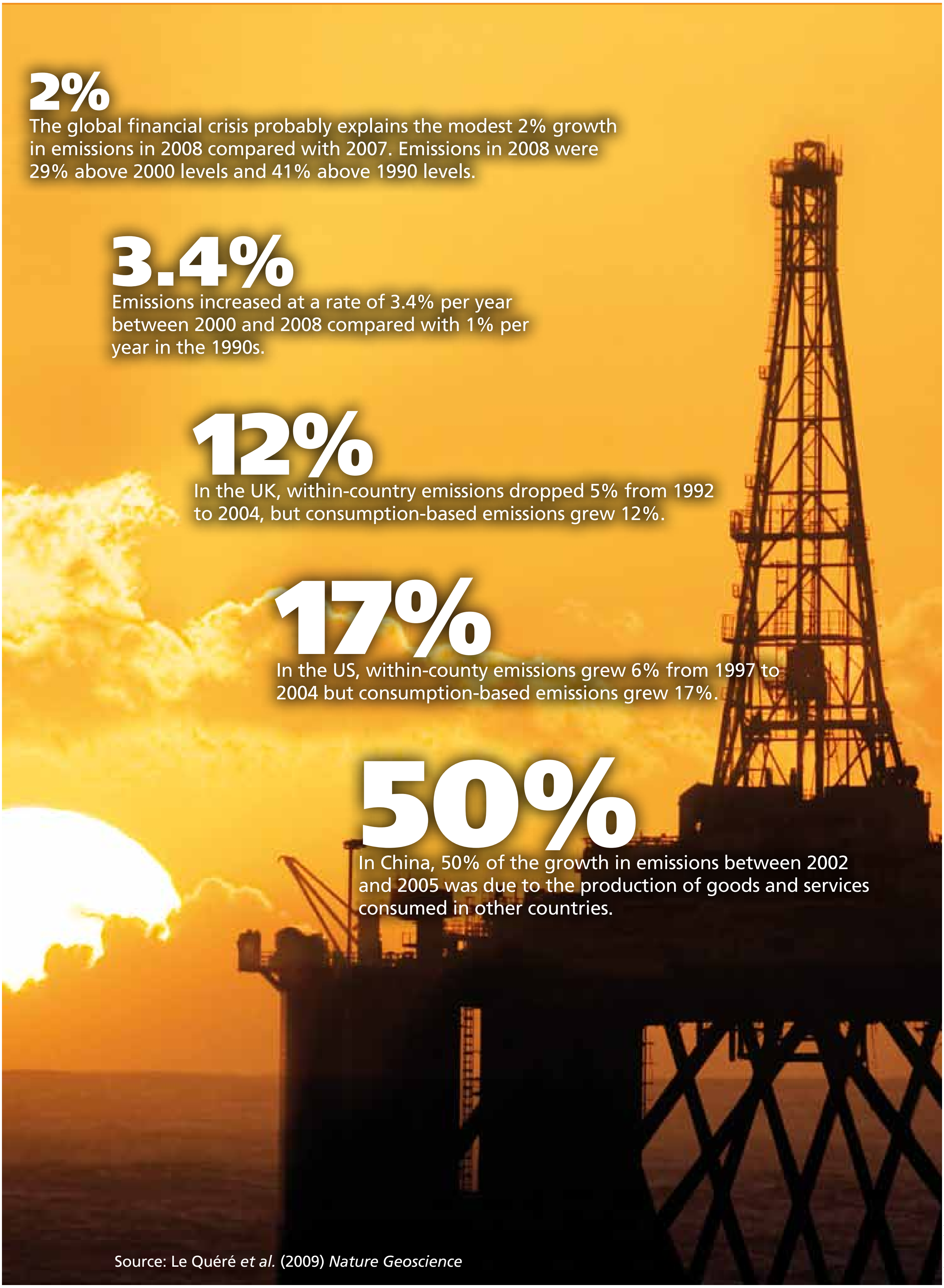
In the past decade, CO_2 emissions increased at a rate of 3.4% per year.

Can we quantify the global CO_2 sinks to such accuracy? To answer this question, we (Le Quéré *et al.* 2009) have put together a global CO_2 budget of all the major sources and sinks of CO_2 for every year from 1959 to 2008 (Figure 1). The aim is to provide information on the year-to-year changes in all aspects of the global CO_2 budget, and to identify the drivers of variability and trends. We used economic data to estimate CO_2 emissions from fossil-fuel combustion and land-use change. Atmospheric CO_2 was measured directly from a network of around 100 stations. We quantified the evolution of the land and ocean CO_2 sinks with the help of models. All models included key processes like plant productivity and respiration on land and circulation, chemical reactions and biological productivity in the ocean. All models were forced by increasing atmospheric CO_2 and the meteorological conditions corresponding to the time period of study. To minimise the errors, we used the mean of all models and estimated error using model spread.

Missing pieces

What were we looking for? The study compared estimated global CO_2 emissions from fossil-fuel use and land-use change with the annual sum of our best estimate of CO_2 increase in the atmosphere, ocean and land during this period (Figure 2). Of course, in theory the undulations of the two lines on the graph should be identical, but they are not: emissions grew steadily but there is considerable annual variability in the estimated CO_2 stored in the atmosphere, ocean and land. So current knowledge does not account for all emitted CO_2.

Known problems in the CO_2 budget explain most of the mismatch. For instance, in the 1970s, it seems there was more additional CO_2 in the system than emissions indicate. We know that La Niña-like conditions led to unusual cool, wet conditions pre-



2%

The global financial crisis probably explains the modest 2% growth in emissions in 2008 compared with 2007. Emissions in 2008 were 29% above 2000 levels and 41% above 1990 levels.

3.4%

Emissions increased at a rate of 3.4% per year between 2000 and 2008 compared with 1% per year in the 1990s.

12%

In the UK, within-country emissions dropped 5% from 1992 to 2004, but consumption-based emissions grew 12%.

17%

In the US, within-county emissions grew 6% from 1997 to 2004 but consumption-based emissions grew 17%.

50%

In China, 50% of the growth in emissions between 2002 and 2005 was due to the production of goods and services consumed in other countries.

Source: Le Quéré *et al.* (2009) *Nature Geoscience*

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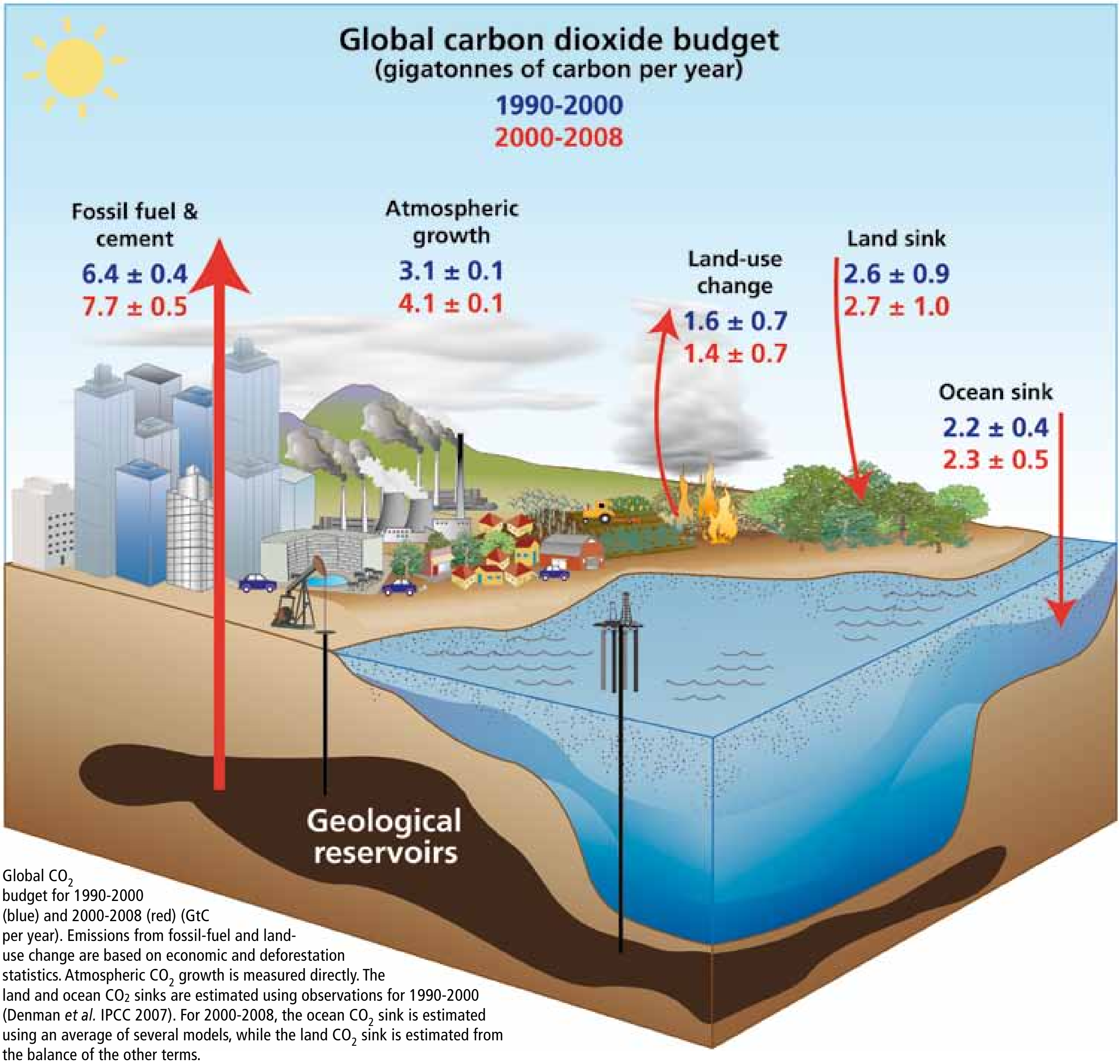


Global CO_2 budget for 1990-2000 (blue) and 2000-2008 (red) (GtC per year). Emissions from fossil-fuel and land-use change are based on economic and deforestation statistics. Atmospheric CO_2 growth is measured directly. The land and ocean CO_2 sinks are estimated using observations for 1990-2000 (Denman *et al.* IPCC 2007). For 2000-2008, the ocean CO_2 sink is estimated using an average of several models, while the land CO_2 sink is estimated from the balance of the other terms.

vailing in the tropics throughout the 1970s causing more carbon to move to the land sink. The models overestimated the land-CO_2 uptake in response to these conditions.

Similarly, the massive Mount Pinatubo volcanic eruption in 1991, which affected climate globally by injecting large volumes of small particles into the upper atmosphere, helps explain the missing CO_2 in the early 1990s. The land models did not account for the increase in available light in the vegetation canopy from enhanced diffusion during and after the eruption.

Excess CO_2 in the late 1990s could in part be a signature of political incentives to clear land in Indonesia.

Finally, the excess CO_2 of the late 1990s appears to be partly a signature of political incentives to clear land in Indonesia that took advantage of the ongoing drought conditions.

Weakening sinks

One interesting result coming out of this analysis was that the trends in accounted CO_2 matched well the trends in emitted CO_2 – both rising at the same rate. This suggests that the processes represented in the models, such as the timescale of penetration of CO_2 in the ocean and the turnover time of soil carbon, are correct to a first order. We can use information on the trends to keep track of the partitioning of the emitted CO_2 between the atmosphere and the sinks. In particular, the fraction of the total CO_2 emissions that remained in the atmosphere – the airborne fraction – is a good indicator of the capacity of the land and ocean sinks to absorb excess CO_2 from the atmosphere. If the sinks weaken, more CO_2 will remain in the atmosphere and amplify global warming.

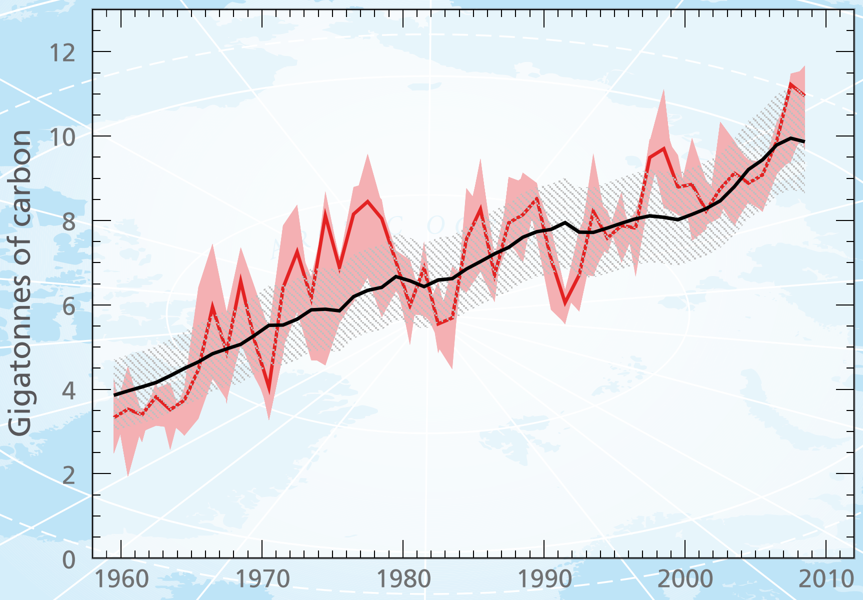
Our analysis of the trend in airborne fraction from this global CO_2 budget shows a likely positive trend of 0.3 percent per year, with a 90 percent probability the trend is above background variability and additional uncertainty due to poorly quantified land-use CO_2 emissions. The models reproduce such a trend and suggest it is a response of the land and ocean sinks to climate variability and climate change for the past 50 years. If the model results are correct in how they represent the processes that reproduced past trends, this supports the existence of a positive feedback between climate and the carbon cycle that was predicted by many carbon-cycle models.

The range of model results is representative of the uncertainty in the known processes. The range of results is smaller than the uncertainty in emissions, which supports the possibility that full accounting of emitted CO_2 is possible, even with existing models. However, to reach such a state requires major improvements in models' year-to-year estimation of CO_2 sinks.

The land models could be improved right away by including the known missing processes. The land and ocean models could also be improved further if the mismatch with observations can be constrained not only globally, but also spatially. Regional information is available from direct measurements in the ocean, and from inverse methods that provide information on the regional variability in the CO_2 fluxes.

We could achieve further improvements if the sinks could be quantified directly from observations. For the ocean, this may be possible with increased data coverage and improved analysis tools. There is little prospect of estimating the land CO_2 sink directly, and thus it will always have to rely on models. Model validation in this context becomes crucial as it ensures the quality of the model estimates.

CO_2 EMISSIONS



Black line: annual cumulative CO_2 emissions from human activities (fossil-fuel combustion, cement production and land-use change). Red line: accounted CO_2 (the sum of the atmospheric CO_2 growth, and the land and ocean CO_2 sinks. Some differences between the black and red curves are due to known problems in the CO_2 budget, particularly associated with the response of land plants to climate variability.

Economic slump

In the past decade, CO_2 emissions increased at a rate of three percent per year. The emissions are projected to decrease in 2009 in response to the global economic downturn. However this decrease should only bring the global emissions down to their 2007 levels. The key to decreasing global emissions in the long term is to decouple energy use from wealth. With the large reorganisation of the world's energy system that is required to stabilise CO_2 in the atmosphere, the global change in CO_2 emissions will be closely scrutinised in the future. There would be enormous benefits to society if the world's scientific community pulls its expertise together to provide information to account for all the CO_2 emitted to the atmosphere. This could assist a peaceful transition to a different economy, but also provide an early warning of how the natural carbon cycle responds to CO_2, climate and other environmental changes.

Between 1959 and 2008, 43% of each year's CO_2 emissions remained in the atmosphere.

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www.globalcarbonproject.org/

MORE INFORMATION

Le Quéré C *et al.* (2009) Trends in the sources and sinks of carbon dioxide. *Nature Geoscience* doi:10.1038/ngeo689.