The global carbon cycle in the Earth System

Shaun Quegan
• Global average temperature and the atmosphere.
• The role of carbon dioxide and methane in climate.
• The global carbon cycle and its components.
What is the Earth’s “natural” temperature?

- Average solar energy on Earth’s surface = 343 watts m\(^{-2}\).
- 6% scattered back to space by atmospheric molecules.
- 10% reflected back by the land and ocean surface.
- Remainder = 288 watts m\(^{-2}\).
- To balance this input, the Earth must emit thermal radiation, whose amount depends on the Earth’s temperature. The balancing temperature of the Earth’s surface is -6°C.

BUT the observed global average temperature near the Earth’s surface is 15°C!
Simple energy balance indicates that the expected average surface temperature should be $-6^\circ$ C, but the observed value is $+15^\circ$ C.

1827: Jean-Baptiste Fourier posited that this was due to energy exchange in the atmosphere.

1860: John Tyndall measured the absorption of infrared radiation by CO$_2$ and water vapour.
A great deal has been written on the influence of the absorption of the atmosphere upon the climate. Tyndall in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variations of temperature that were lessened by this circumstance. Another side of the question, that has long attracted the attention of physicists, is this: Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere? Fourier maintained that the atmosphere acts like the glass in a hot house, because it lets through the light rays of the sun but retains the dark rays from the ground. This idea was elaborated by Pouillet; and Langley was by some of his researches led to the view, that the temperature of the earth under direct sunshine, even though our atmosphere were present as now, would probably fall to – 200 °C., if that atmosphere did not possess the

* Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December 1895. Communicated by the Author.

† “Heat a mode of motion,” 2nd ed. p.405 (Lond.,1865).
§ Compress rendus, t. vii. p41 (1838).

Estimate of 5-7° C for a doubling of CO₂ has stood the test of time!
The Greenhouse Effect

IPCC, 2007: “Without the natural greenhouse effect, the average temperature of the Earth’s surface would be below 0ºC. This natural greenhouse effect makes life as we know it possible. However, human activities, primarily the burning of fossil fuels and the clearing of forests have greatly intensified the natural greenhouse effect, causing global warming.”
Atmospheric $\text{CO}_2$: the Keeling Curve

1940: G. S. Callendar calculated warming due to burning fossil fuels.
Past climate and CO$_2$

Petit et al., Nature, 1999
CO₂, NH₄ and N₂O in the last 1000 years

From: IPCC, Climate Change, 2001
## Greenhouse gases

<table>
<thead>
<tr>
<th>Gas</th>
<th>Radiative efficiency (Wm$^{-2}$ppb$^{-1}$)</th>
<th>Lifetime (years)</th>
<th>Global Warming Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Time horizon</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20 yrs</td>
</tr>
<tr>
<td>CO$_2$</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>$3.7 \times 10^{-4}$</td>
<td>12.0</td>
<td>62</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>$3.1 \times 10^{-3}$</td>
<td>114</td>
<td>275</td>
</tr>
</tbody>
</table>

IPCC, Climate Change, 2001
Radiative forcing components

Anthropogenic and natural forcing of the climate for the year 2000, relative to 1750

Global mean radiative forcing (Wm^-2)

- Greenhouse gases
  - Halocarbons
  - N₂O
  - CH₄
- Tropospheric ozone
- Stratospheric ozone
- Sulphate
- Organic carbon from fossil fuel burning
- Biomass burning
- Mineral Dust
- Aviation Contrails Cirrus
- Solar
- Aerosols + clouds
- Land use (albedo only)

The height of a bar indicates a best estimate of the forcing, and the accompanying vertical line a likely range of values. Where no bar is present the vertical line only indicates the range in best estimates with no likelihood.

LEVEL OF SCIENTIFIC UNDERSTANDING

High  Medium  Medium  Low  Very low  Very low  Very low  Very low  Very low  Very low
Radiative forcing components

- CO₂
- Halocarbons
- CH₄
- Stratospheric ozone
- Tropospheric ozone
- Stratospheric water vapour
- Black carbon on snow
- Direct effect
- Cloud albedo effect
- Linear contrails
- Solar irradiance
- Greenhouse gases
- Ozone
- Albedo
- Net anthropogenic component
Natural and anthropogenic components of the carbon cycle

- **Black** = preindustrial sizes of reservoirs
- **Red** = changes resulting from human activities

Units: 1 Pg = $10^9$ t = 1 Gt

Atomic weight of O = 16
Atomic weight of C = 12
To convert C to CO$_2$ multiply by $44/12 = 11/3$
Photosynthesis began at least 2.7 billion years ago, and provides a route for removing carbon dioxide from the atmosphere:

$$\text{CO}_2 + 2\text{H}_2\text{O} = (\text{CH}_2\text{O}) + \text{H}_2\text{O} + \text{O}_2$$
Keeling CO2 plots
Anthropogenic perturbation of the global carbon cycle

Perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2007–2016 (GtCO₂/yr)

The budget imbalance is the difference between the estimated emissions and sinks.

Source: CDIAC; NOAA-ESRL; Le Quéré et al 2017; Global Carbon Budget 2017
Balancing the Carbon Budget
<table>
<thead>
<tr>
<th>Sources</th>
<th>Sinks</th>
</tr>
</thead>
<tbody>
<tr>
<td>34.4 ± 1.8 GtCO₂/yr (88%)</td>
<td>17.2 ± 0.4 GtCO₂/yr (46%)</td>
</tr>
<tr>
<td>4.8 ± 2.6 GtCO₂/yr (12%)</td>
<td>11.0 ± 2.9 GtCO₂/yr (30%)</td>
</tr>
<tr>
<td>8.8 ± 1.8 GtCO₂/yr (24%)</td>
<td></td>
</tr>
</tbody>
</table>

Budget Imbalance = difference between estimated sources & sinks

2.2 ± 4.3 GtCO₂/yr (6%)
Carbon emissions are partitioned among the atmosphere and carbon sinks on land and in the ocean. The “imbalance” between total emissions and total sinks reflects the gap in our understanding.

CO$_2$: emissions vs atmospheric increase

Seasonal variation of atmospheric $\text{CO}_2$ concentration

Weekly $\text{CO}_2$ concentration measured at Mauna Loa stayed above 400ppm throughout 2016 and is forecast to average 406.8 in 2017.

Forecasts are an update of Betts et al 2016. The deviation from monthly observations is 0.24 ppm (RMSE). Updates of this figure are available, and another on the drivers of the atmospheric growth.

Breakdown of global emissions by country

Emissions from OECD countries are about the same as in 1990
Emissions from non-OECD countries have increased rapidly in the last decade

Source: CDIAC; Le Quéré et al 2017; Global Carbon Budget 2017
Land-use change emissions

Land-use change emissions are highly uncertain. Higher emissions in 2016 are linked to increased fires during dry El Niño conditions in tropical Asia.
Total global emissions

Total global emissions: 40.8 ± 2.7 GtCO₂ in 2016, 52% over 1990
Percentage land-use change: 42% in 1960, 12% averaged 2007-2016

Land-use change estimates from two bookkeeping models, using fire-based variability from 1997
Source: CDIAC, Houghton and Nassikas 2017; Hansis et al 2015; van der Werf et al. 2017; Le Quéré et al 2017; Global Carbon Budget 2017
Atmospheric concentration

The atmospheric concentration growth rate has shown a steady increase. The high growth in 1987, 1998, & 2015-16 reflect a strong El Niño, which weakens the land sink.

Source: NOAA-ESRL; Global Carbon Budget 2017
The ocean carbon sink continues to increase 8.7±2 GtCO₂/yr for 2007–2016 and 9.6±2 GtCO₂/yr in 2016.

Source: SOCATv5; Bakker et al 2016; Le Quéré et al 2017; Global Carbon Budget 2017

Individual estimates from: Aumont and Bopp (2006); Buitenhuis et al. (2010); Doney et al. (2009); Hauck et al. (2016); Ilyina et al. (2013); Landschützer et al. (2016); Law et al. (2017); ; Rödenbeck et al. (2014). Séférian et al. (2013); Schwinger et al. (2016). Full references provided in Le Quéré et al. (2017).
Terrestrial sink

The land sink was $11.2 \pm 3 \text{ GtCO}_2/\text{yr}$ during 2007-2016 and $10 \pm 3 \text{ GtCO}_2/\text{yr}$ in 2016.

Total CO$_2$ fluxes on land (including land-use change) are constrained by atmospheric inversions.

Source: Le Quéré et al 2017; Global Carbon Budget 2017

Individual estimates from: Chevallier et al. (2005); Clarke et al. (2011); Guimberteau et al. (2017); Hansis et al. (2015); Haverd et al. (2017); Houghton and Nassikas (2017); Jain et al. (2013); Kato et al. (2013); Keller et al. (2017); Krinner et al. (2005); Melton and Arora (2016); Oleson et al. (2013); Reick et al. (2013); Rodenbeck et al. (2003); Sitch et al. (2003); Smith et al. (2014); Tian et al. (2015); van der Laan-Luijkx et al. (2017); Woodward et al. (1995); Zaehle and Friend (2010). Full references provided in Le Quéré et al. (2017).
The land component of the C cycle: natural fluxes

- **Gross Primary Production (GPP)**: 120 Gt C
- **Net Primary Production (NPP)**: 60 Gt C
- **Net Ecosystem Production (NEP)**: 5 Gt C
- **Net Biome Production (NBP)**: 2 Gt C

Fluxes include:
- Photosynthesis
- Plant respiration
- Soil respiration
- Disturbance
The ocean component of the C cycle
After carbon dioxide (CO₂), methane (CH₄) is the second most important greenhouse gas contributing to human-induced climate change.

For a time horizon of 100 years, CH₄ has a Global Warming Potential 28 times larger than CO₂.

Methane is responsible for 20% of the global warming produced by all greenhouse gases so far.

The concentration of CH₄ in the atmosphere is 150% above pre-industrial levels (cf. 1750).

The atmospheric life time of CH₄ is 9±2 years, making it a good target for climate change mitigation.

Methane also contributes to tropospheric production of ozone, a pollutant that harms human health and ecosystems.

Methane also leads to production of water vapor in the stratosphere by chemical reactions, enhancing global warming.

Sources: Saunois et al. 2016, ESDD; Kirschke et al. 2013, NatureGeo.; IPCC 2013 5AR; Voulgarakis et al., 2013
Global Methane Budget 2003-2012

Global Carbon Project

http://www.globalcarbonatlas.org
CH₄ Atmospheric Growth Rate, 1983-2012

- Slowdown of atmospheric growth rate before 2006
- Resumed increase after 2006

*Source: Saunois et al. 2016, ESSD (Fig. 1)*
Mapping of the largest methane source categories

Source: Saunois et al. 2016, ESSD (Fig 3)
Summary

• The Earth responds as a complex system to a wide range of forcings, several of which are anthropogenic.
• The mean global temperature of the Earth is strongly correlated with and affected by the concentration of atmospheric CO$_2$.
• Greenhouse gas forcing has changed sharply since the industrial revolution and the current atmospheric trace gas make-up is well outside the natural limits seen in last 500000 years.
• A central role is played by the Earth’s carbon cycle, mainly through CO$_2$ but also through CH$_4$.
• The land and ocean play roughly equal parts in mitigating the build-up of CO$_2$ in the atmosphere.