→ EARTH OBSERVATION SUMMER SCHOOL

Earth System Monitoring & Modelling

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The global carbon cycle in the Earth System

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Lecture content

- 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!

Pioneers of Climate Change research

Simple energy balance indicates that the expected average surface temperature should be -6º C, but the observed value is +15º 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.

Carbon dioxide and the greenhouse effect

THE LONDON, EDINBURGH AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND JOURNAL OF SCIENCE

[FIFTH SERIES APRIL 1896]

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* By Prof. SVANTE ARRHENIUS*.

1. Introduction: Observations of Langley on Atmospherical Absorption.

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

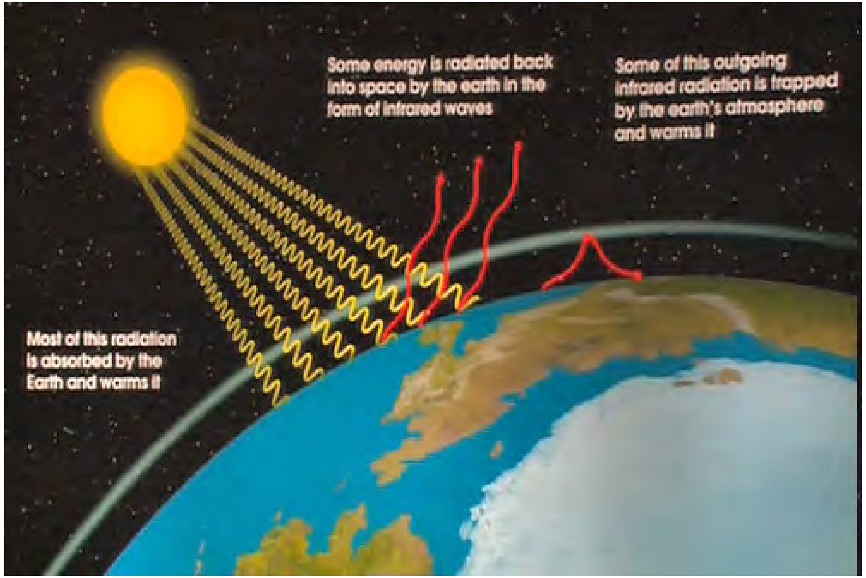
* Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December 1895. Communicated by the Author.

† "Heat a mode of motion," 2nd ed. p.405 (Lond.,1865).
‡ *Mem. de l'Ac. R. d. Sci. de l'Inst. de France,* t. vii. 1827.
§ *Compress rendus,* t. vii. p41 (1838).

Estimate of 5-7^{o} C for a doubling of CO_2 has stood the test of time !

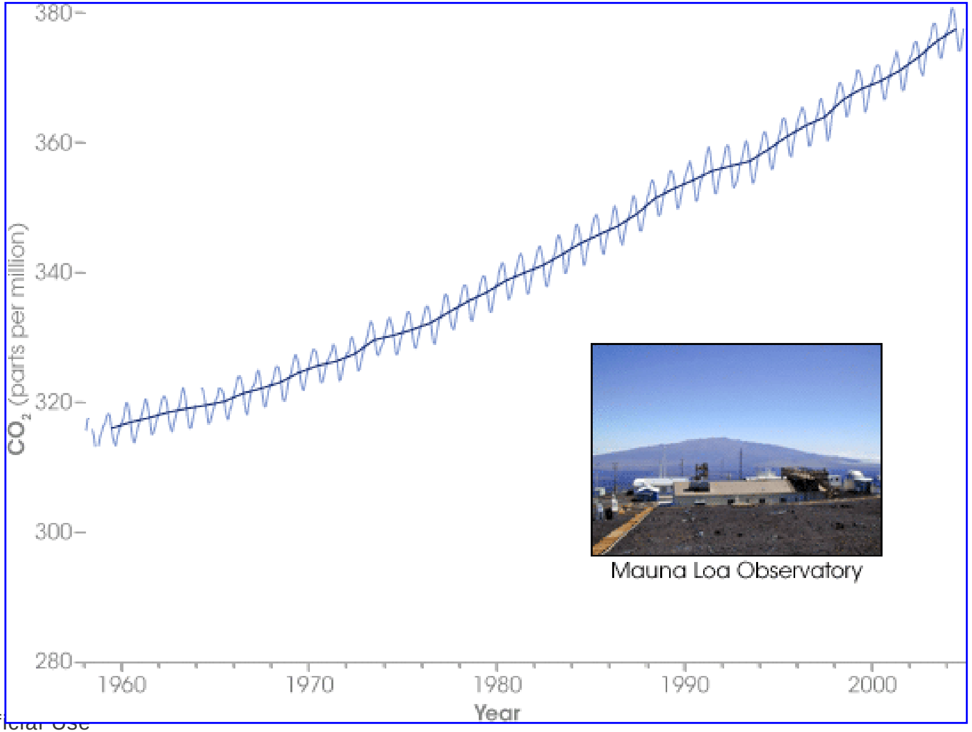
The Greenhouse Effect

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.”



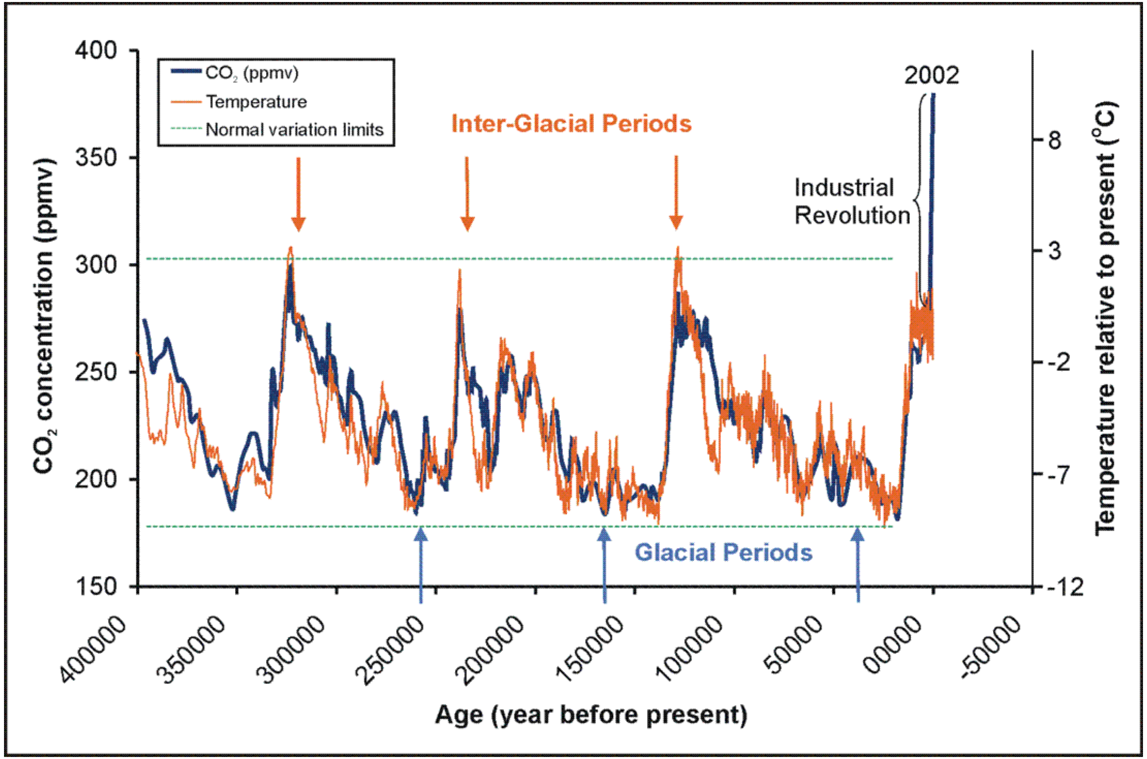
Atmospheric CO_2: the Keeling Curve

1940: G. S. Callendar calculated warming due to burning fossil fuels.



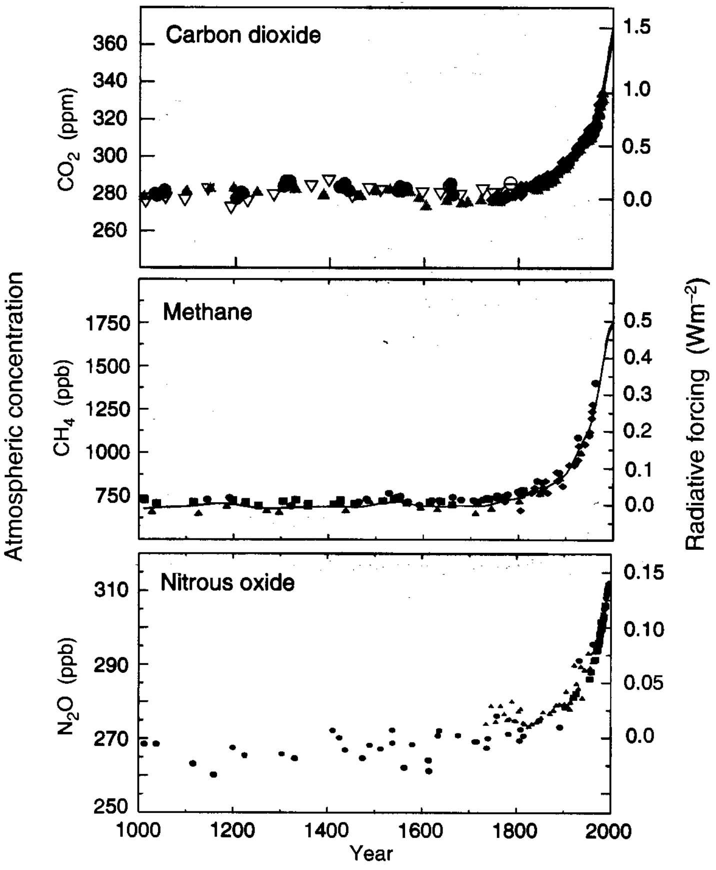
Charles David Keeling (1928-2005)

Past climate and CO_2



Petit et al., Nature, 1999

CO_2, NH_4 and N_2O in the last 1000 years



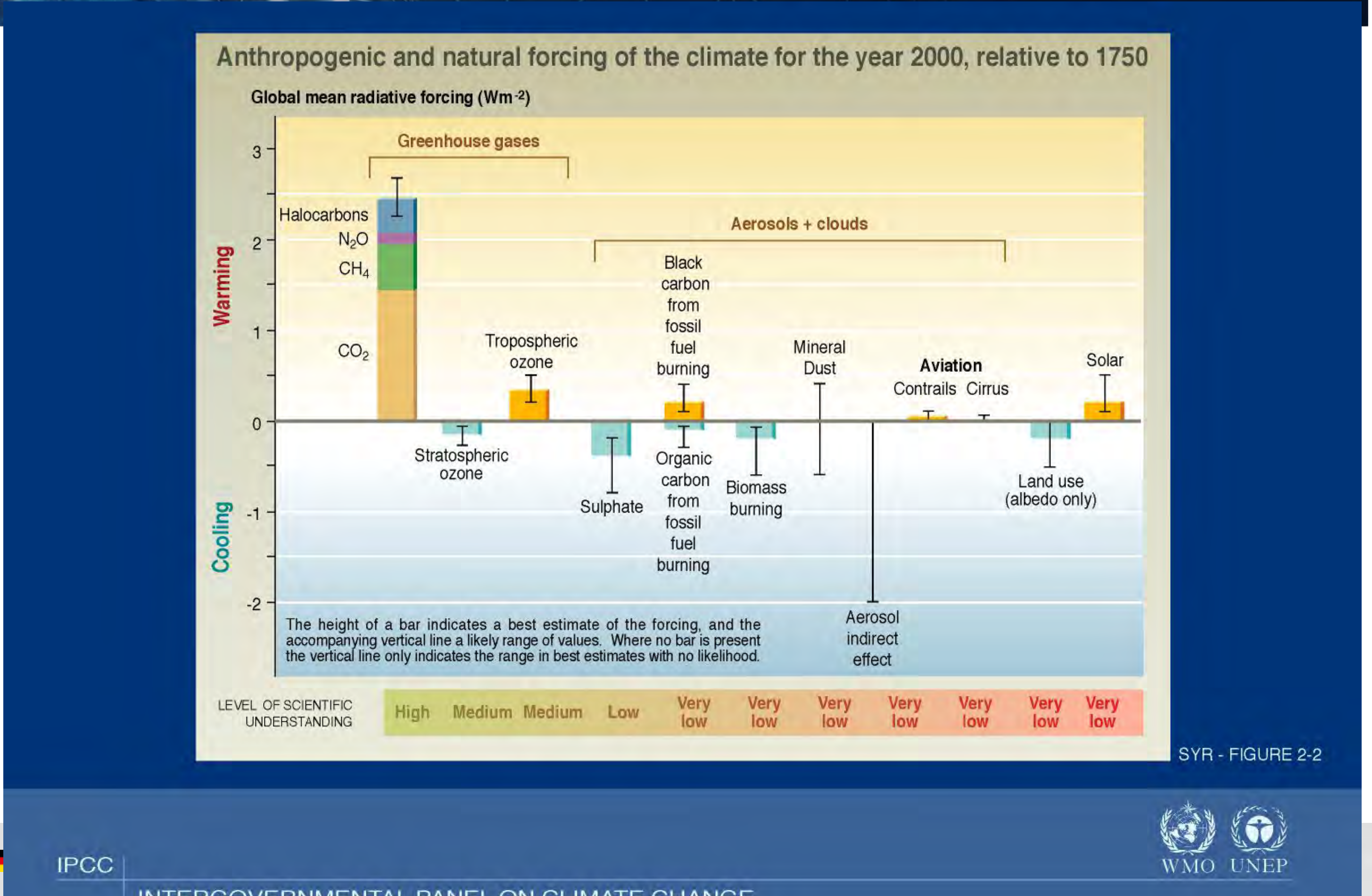
From: IPCC, Climate Change, 2001

Greenhouse gases

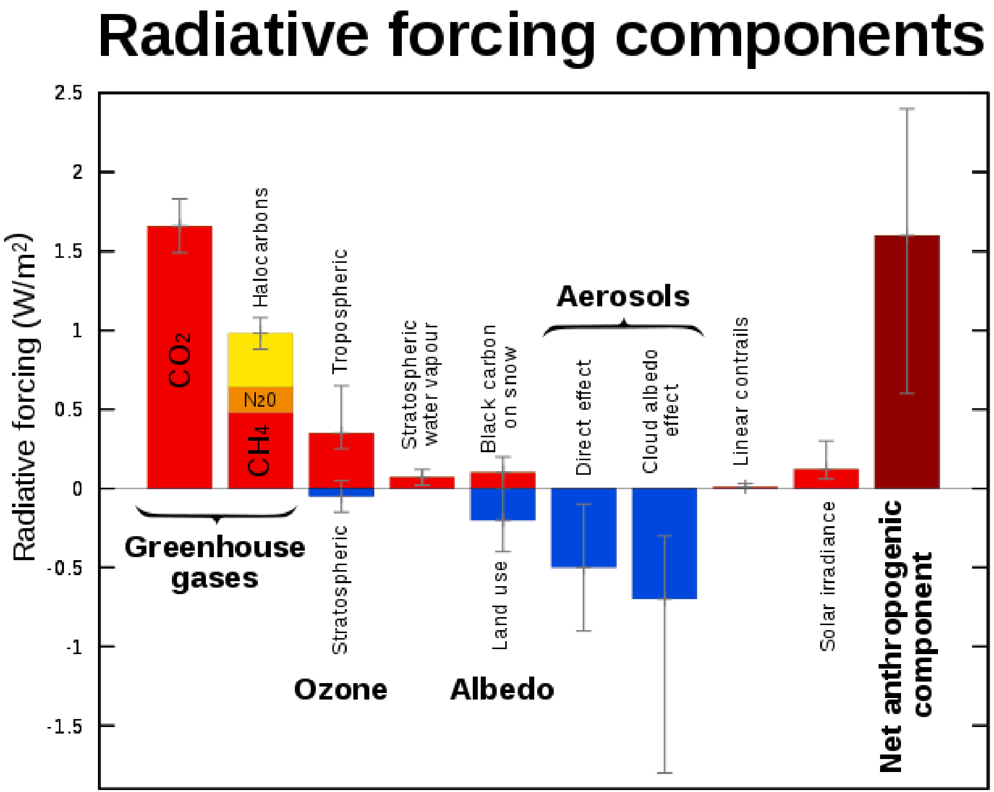
Gas	Radiative efficiency ($Wm^{-2}ppb^{-1}$)	Lifetime (years)	Global Warming Potential Time horizon		
			20 yrs	100 yrs	500 yrs
CO_2			1	1	1
CH_4	3.7×10^{-4}	12.0	62	23	7
N_2O	3.1×10^{-3}	114	275	296	156

IPCC, Climate Change, 2001

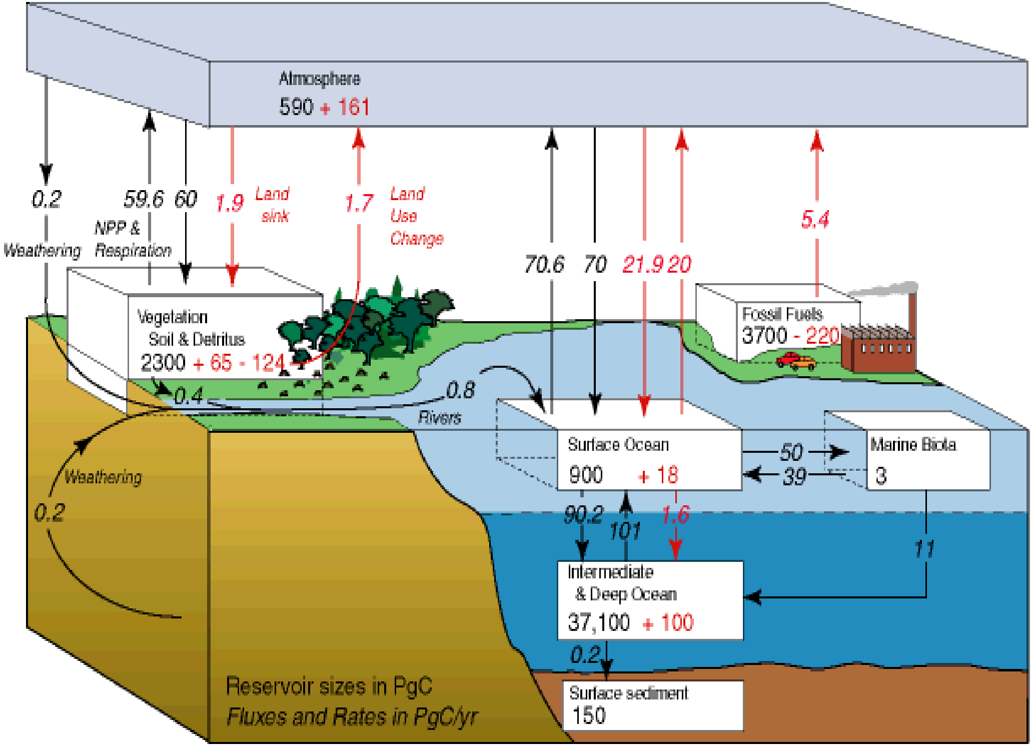
Radiative forcing components



Radiative forcing components



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

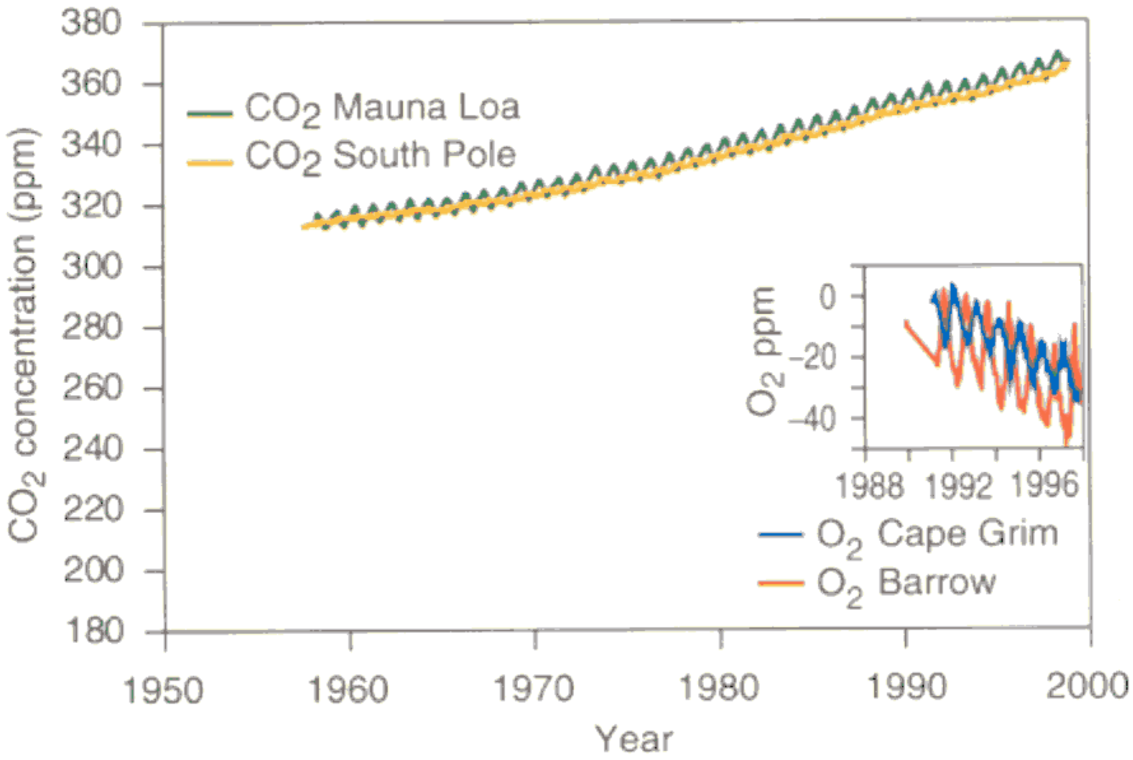
Sarmiento, J.L. and Gruber, N. (2002).

Photosynthesis as a carbon sink

Photosynthesis began at least 2.7 billion years ago, and provides a route for removing carbon dioxide from the atmosphere:

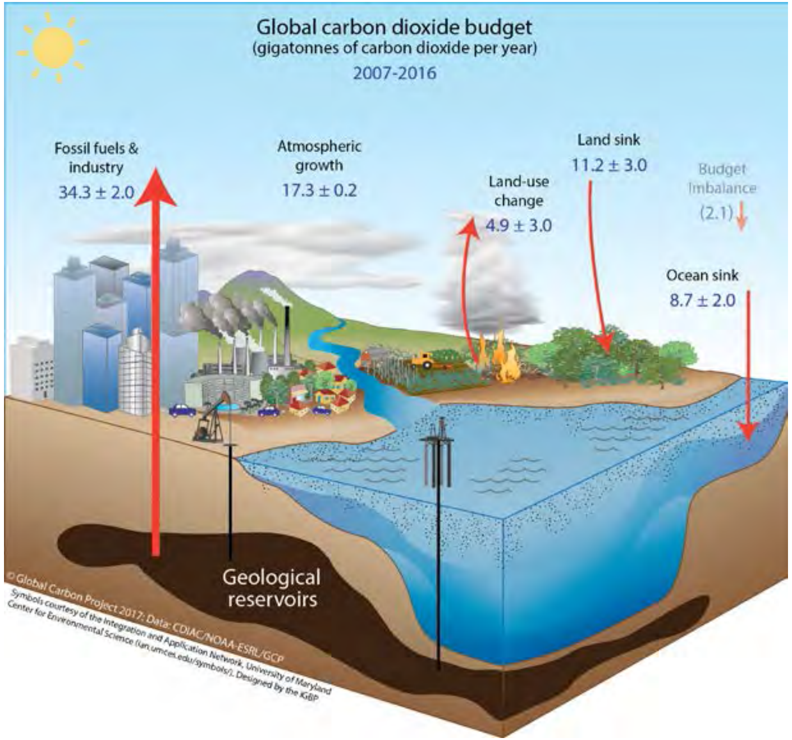
$$CO_2 + 2H_2O = (CH_2O) + H_2O + O_2$$

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 ($GtCO_2$/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

Fate of anthropogenic CO_2 emissions (2007–2016)

Sources = Sinks

34.4 ±1.8 $GtCO_2$/yr
88%

4.8 ± 2.6 $GtCO_2$/yr
12%

17.2 ±0.4 $GtCO_2$/yr
46%

11.0 ± 2.9 $GtCO_2$/yr
30%

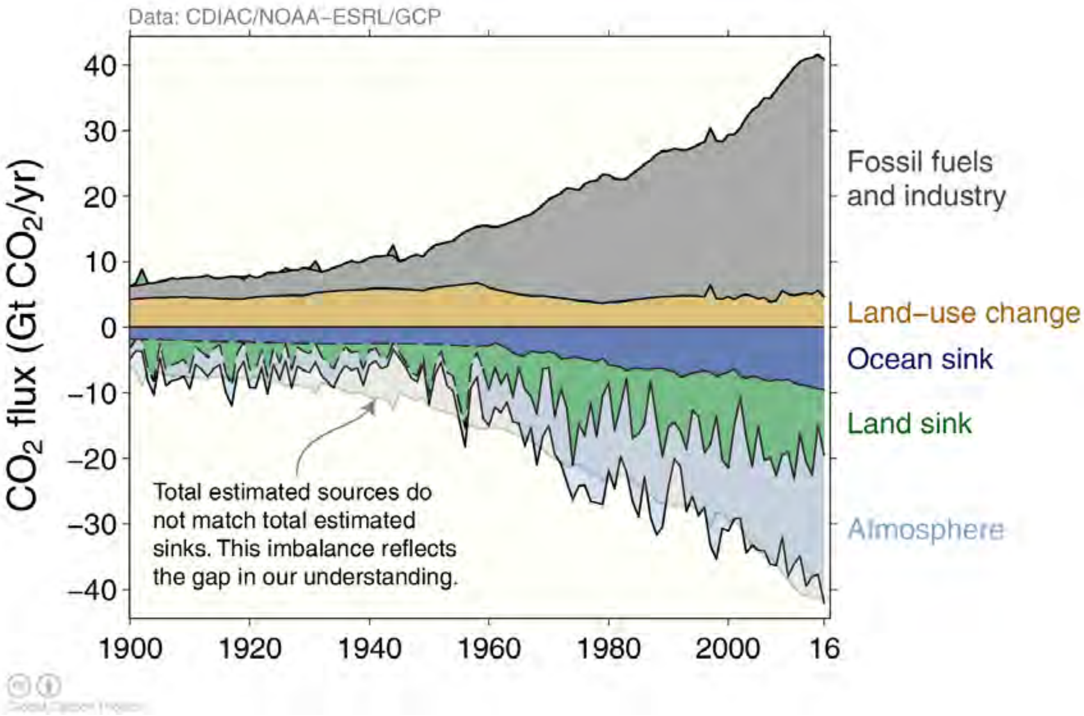
8.8 ± 1.8 $GtCO_2$/yr
24%

Budget Imbalance = difference between estimated sources & sinks

2.2 ± 4.3 $GtCO_2$/yr
6%

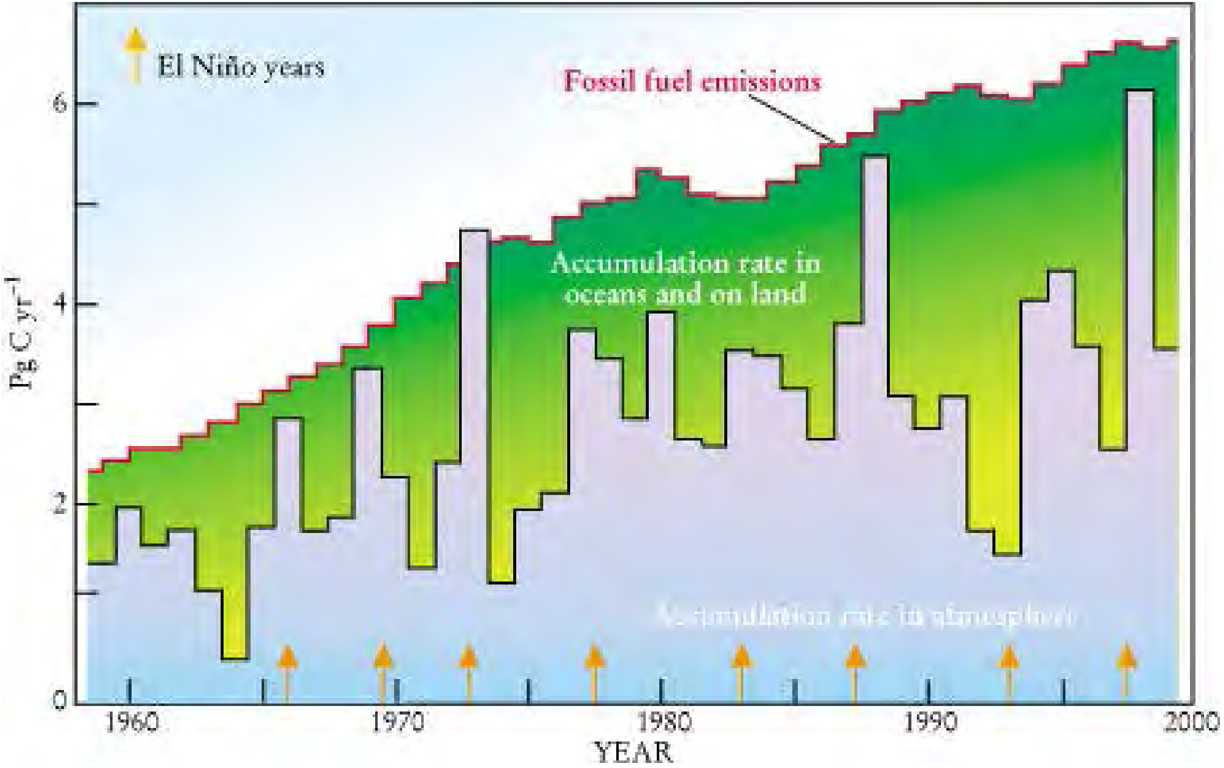
Global carbon budget

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



Source: CDIAC; NOAA-ESRL; Houghton and Nassikas 2017; Hansis et al 2015; Joos et al 2013; Khatiwala et al. 2013; DeVries 2014; Le Quéré et al 2017; Global Carbon Budget 2017

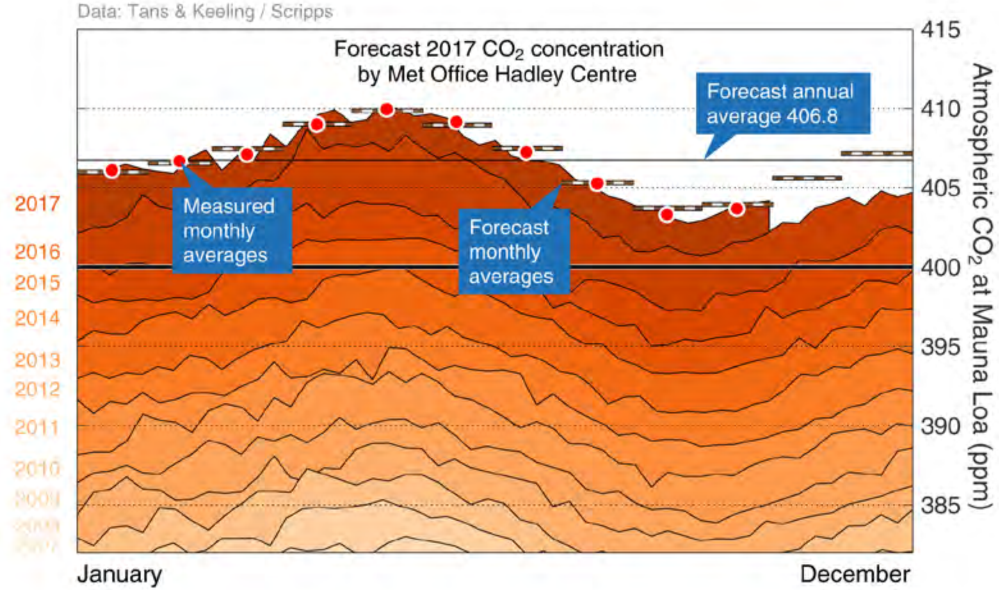
CO_2: emissions vs atmospheric increase



From: ‘Sinks for Anthropogenic Carbon’, Physics Today, August 2002, Jorge L. Sarmiento and Nicolas Gruber

Seasonal variation of atmospheric CO_2 concentration

Weekly CO_2 concentration measured at Mauna Loa stayed above 400ppm throughout 2016 and is forecast to average 406.8 in 2017

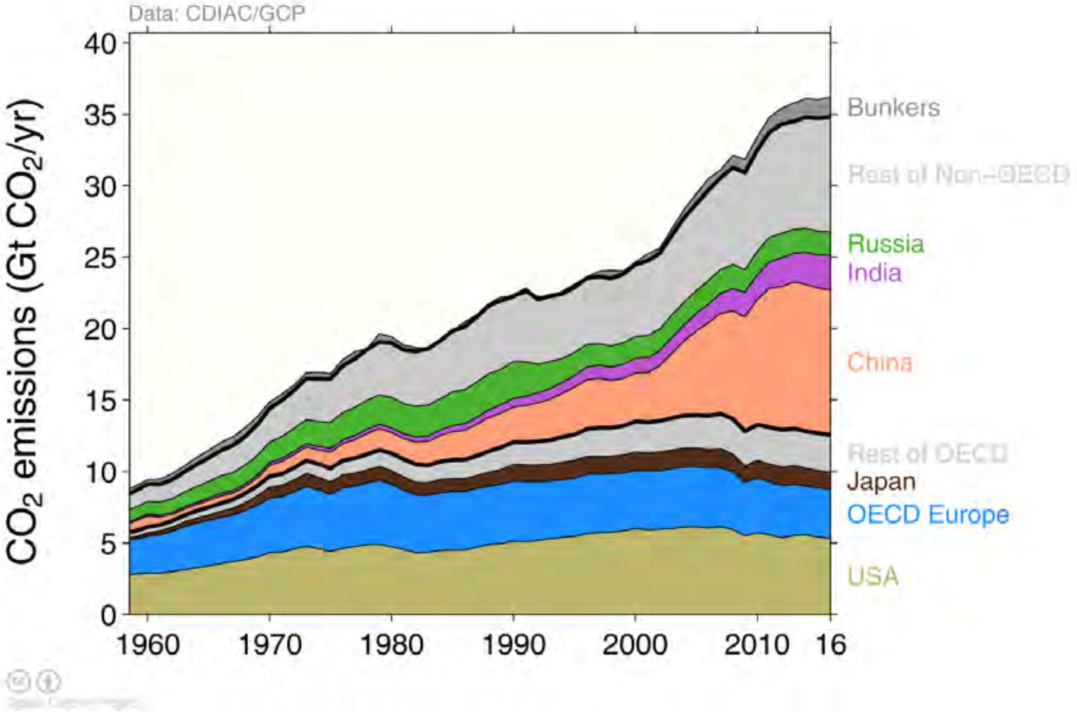


Forecasts are an update of Betts et al 2016. The deviation from monthly observations is 0.24 ppm (RMSE).
Updates of this figure are available, and another on the drivers of the atmospheric growth

Source: Tans and Keeling (2017), NOAA-ESRL, Scripps Institution of Oceanography

Breakdown of global emissions by country

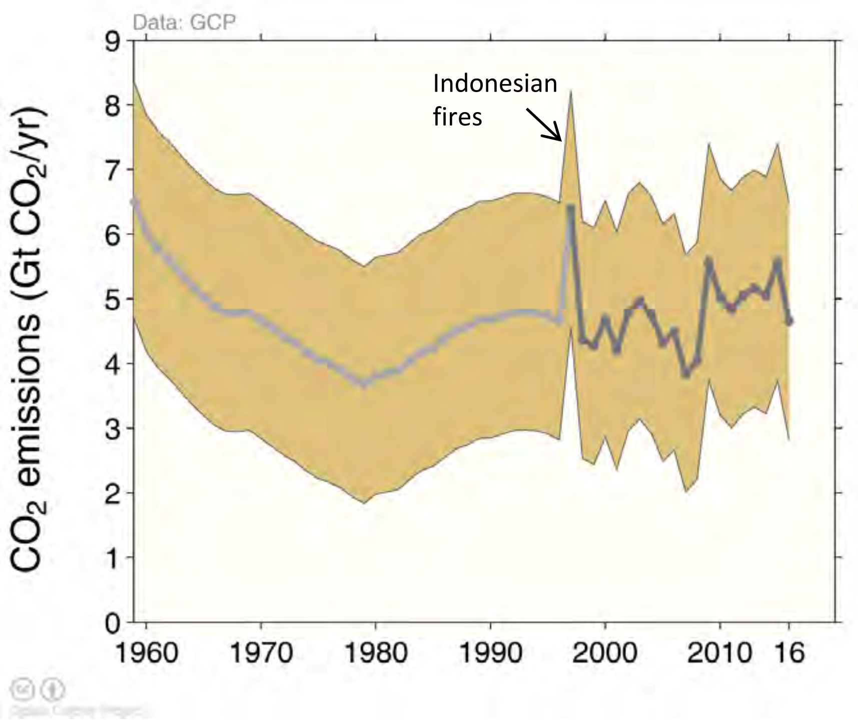
Emissions from OECD countries are about the same as in 1990
Emissions from non-OECD countries have increased rapidly in the last decade



Source: [CDIAC](); [Le Quéré et al 2017](); [Global Carbon Budget 2017]()

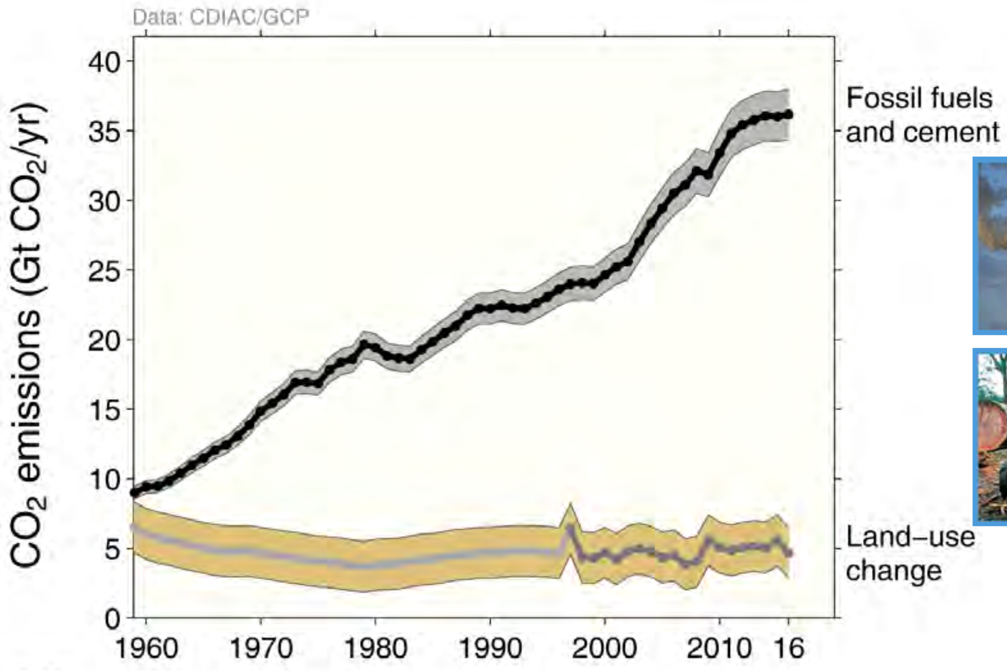
Land-use change emissions

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

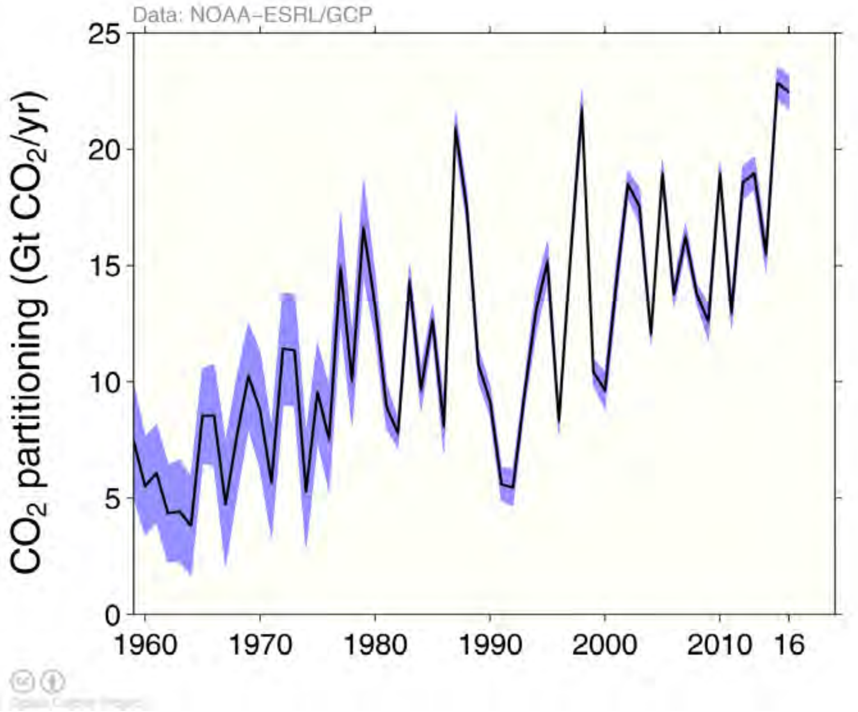
Total global emissions: 40.8 ± 2.7 $GtCO_2$ in 2016, 52% over 1990
Percentage land-use change: 42% in 1960, 12% averaged 2007-2016



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

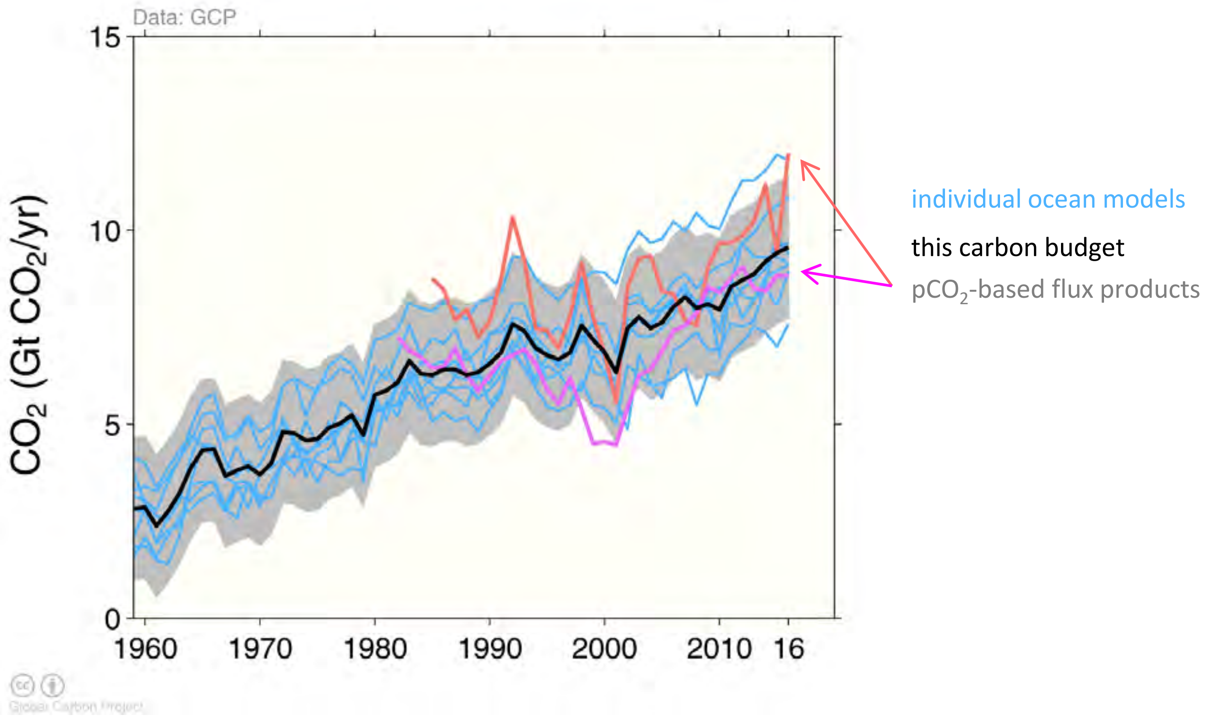
The atmospheric concentration growth rate has shown a steady increase
The high growth in 1987, 1998, & 2015-16 reflect a strong El Niño, which weakens the land sink



Source: NOAA-ESRL; Global Carbon Budget 2017

Ocean sink

The ocean carbon sink continues to increase
8.7±2 $GtCO_2$/yr for 2007–2016 and 9.6±2 $GtCO_2$/yr in 2016

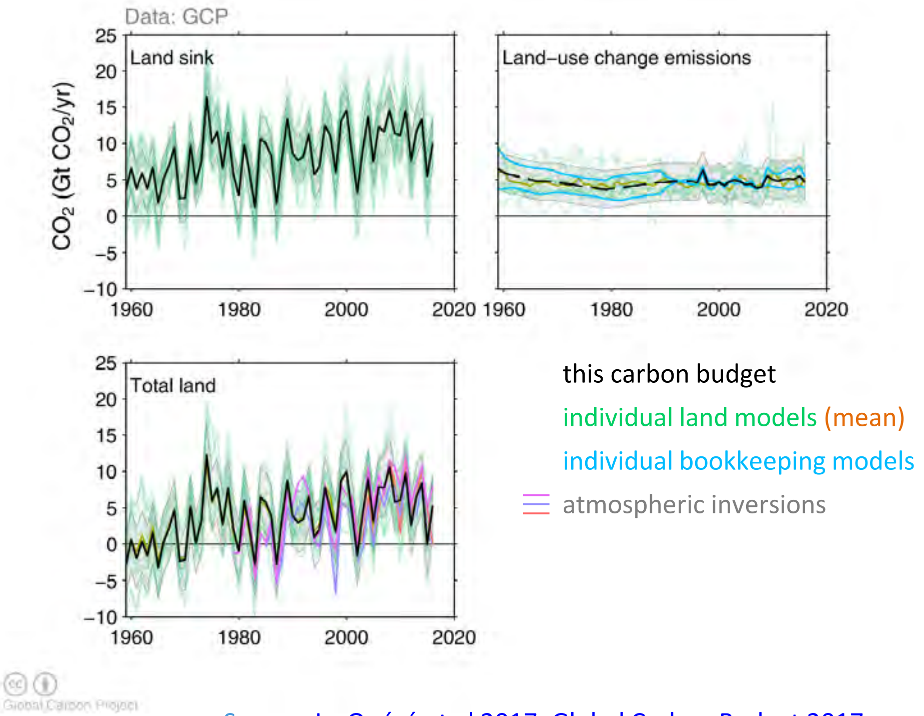


Source: [SOCATv5]; [Bakker et al 2016]; [Le Quéré et al 2017]; [Global Carbon Budget 2017]

Individual estimates from: Aumont and Bopp (2006); Buitenhuis et al. (2010); Doney et al. (2009); Hauck et al. (2016); Ilyiana 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

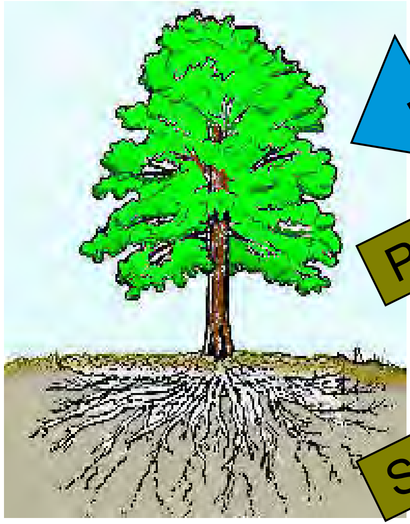
The land sink was 11.2±3 GtCO2/yr during 2007-2016 and 10±3 $GtCO_2$/yr in 2016
Total CO_2 fluxes on land (including land-use change) are constrained by atmospheric inversions

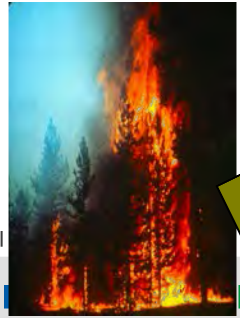


Source: [Le Quéré et al 2017](); [Global Carbon Budget 2017]()

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





photosynthesis

Plant respiration

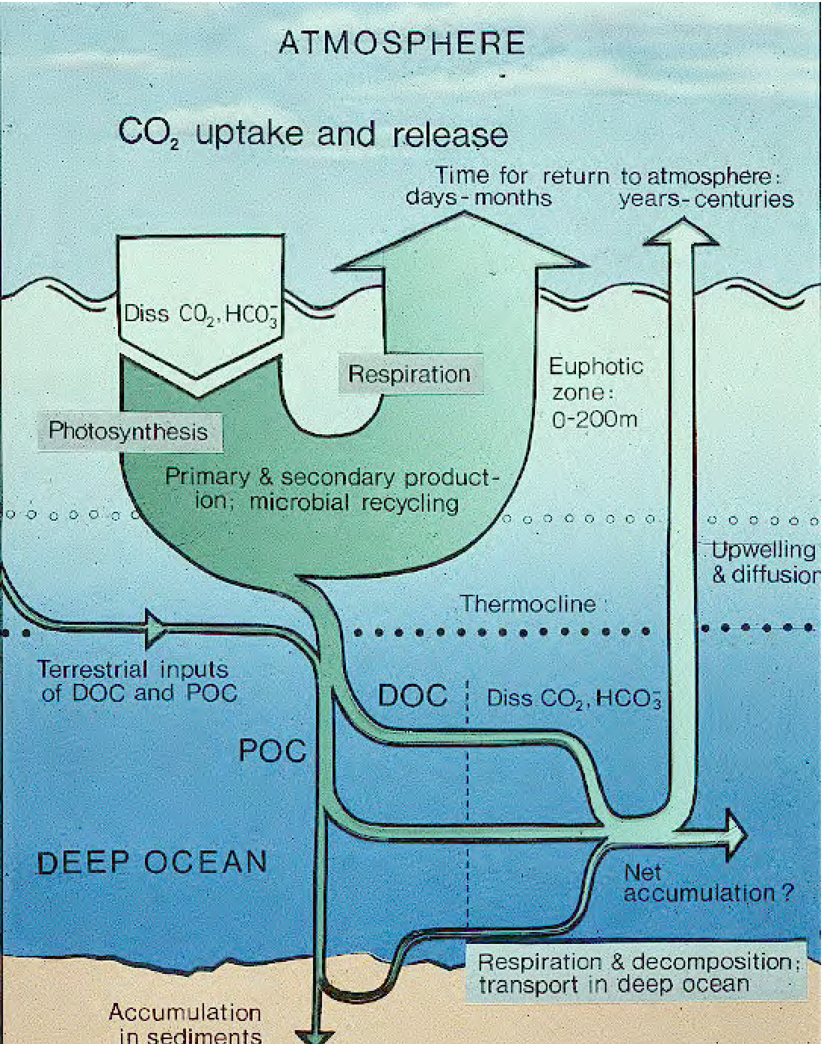
Soil respiration

disturbance

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

Net global fluxes

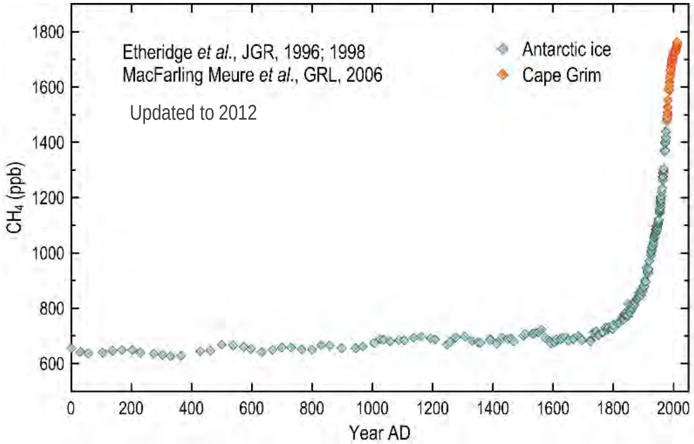
The ocean component of the C cycle



The Global Methane Budget

The methane context

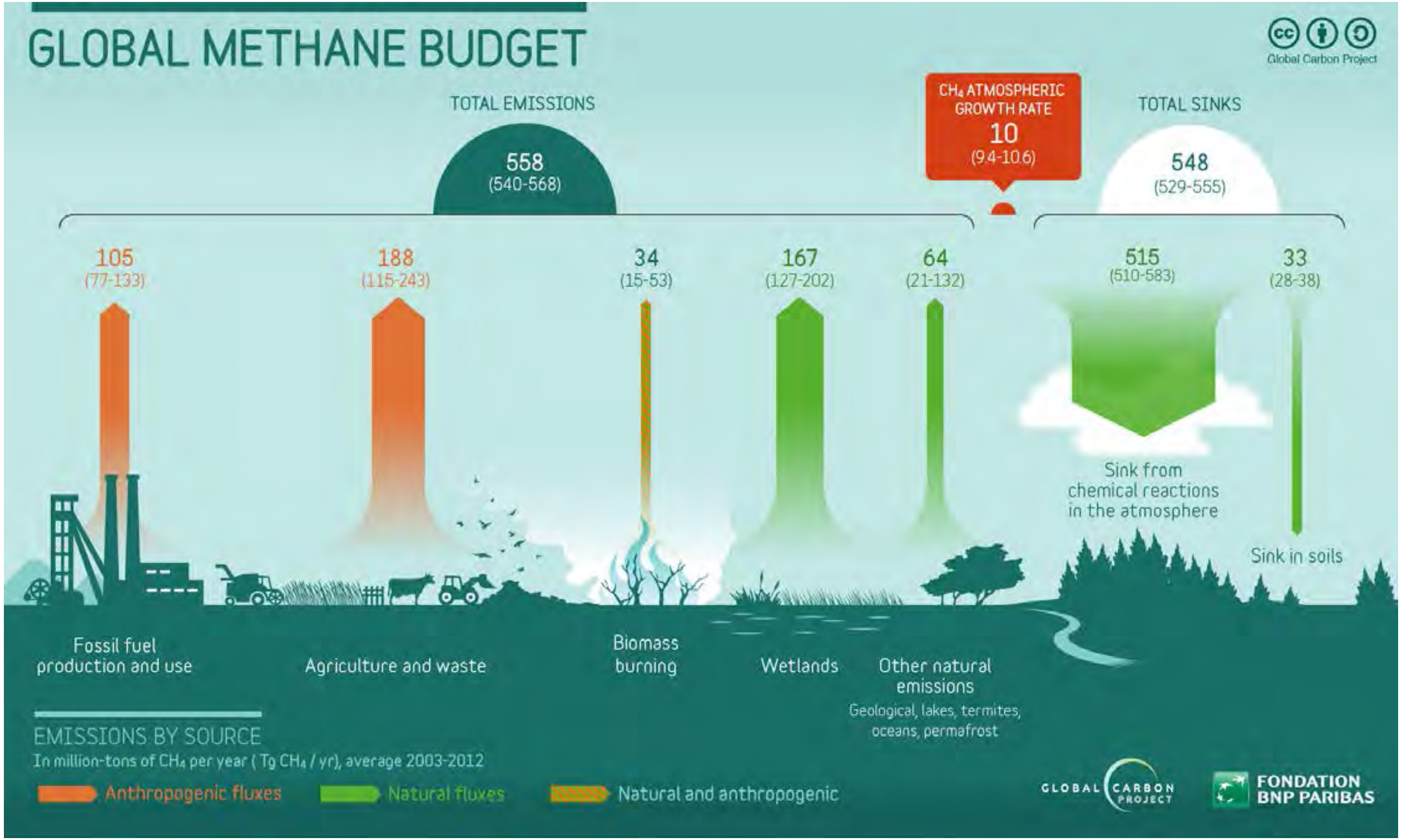
- After carbon dioxide (CO_2), methane (CH_4) is the second most important greenhouse gas contributing to human-induced climate change.
- For a time horizon of 100 years, CH_4 has a Global Warming Potential 28 times larger than CO_2.
- Methane is responsible for 20% of the global warming produced by all greenhouse gases so far.
- The concentration of CH_4 in the atmosphere is 150% above pre-industrial levels (cf. 1750).
- The atmospheric life time of CH_4 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.

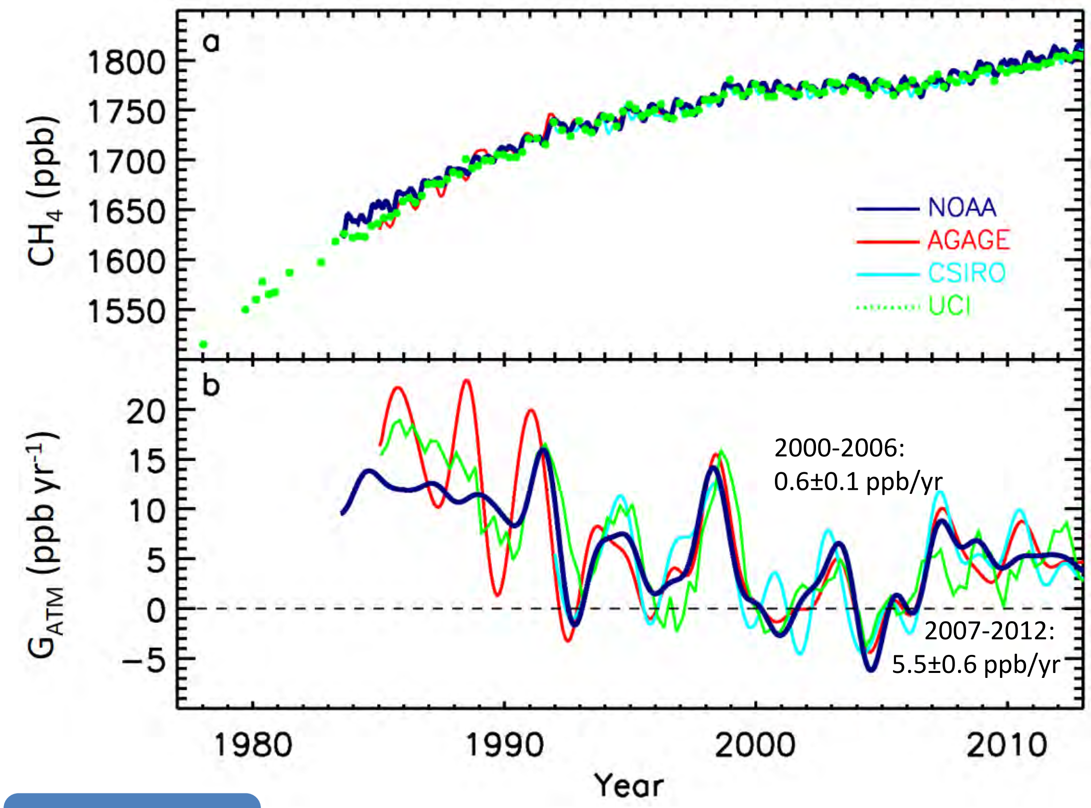
Sources : Saunois et al. 2016, ESDD; Kirschke et al. 2013, NatureGeo.; IPCC 2013 5AR; Voulgarakis et al., 2013

Global Methane Budget 2003-2012



http://www.globalcarbonatlas.org

CH_4 Atmospheric Growth Rate, 1983-2012

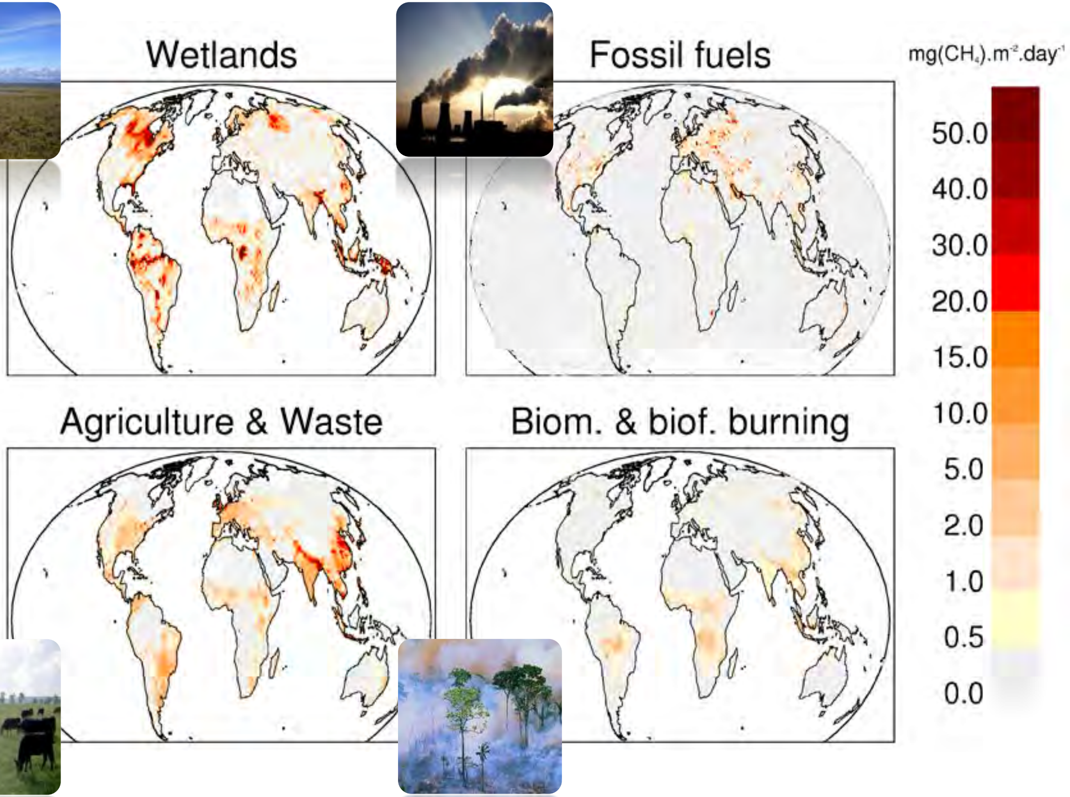


- Slowdown of atmospheric growth rate before 2006
- Resumed increase after 2006

Atmospheric observations

Source: Saunois et al. 2016, ESSD (Fig. 1)

Mapping of the largest methane source categories



Emission inventories

Biogeochemistry models & data-driven methods

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.