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Key Finding 1: The Observed Increases in Atmospheric CO_2 and CH_4

- CO_2 has increased by 40% since preindustrial times. (From 280 ppm to over 400 ppm)
- CH_4 has increased by 160% since preindustrial times. (From 700 ppb to over 1,850 ppb)
- The current understanding of sources and sinks of atmospheric carbon indicates that human activities, especially fossil fuel combustion, are responsible for these increases.

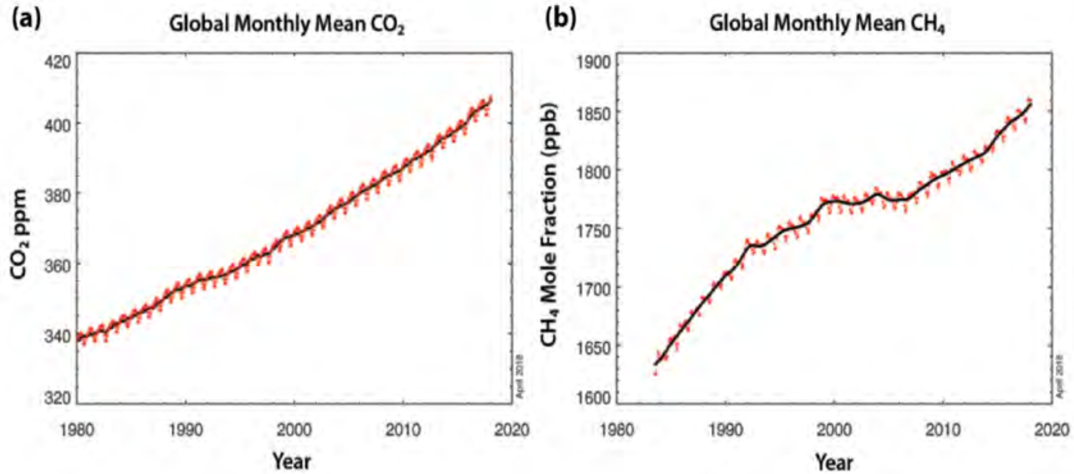
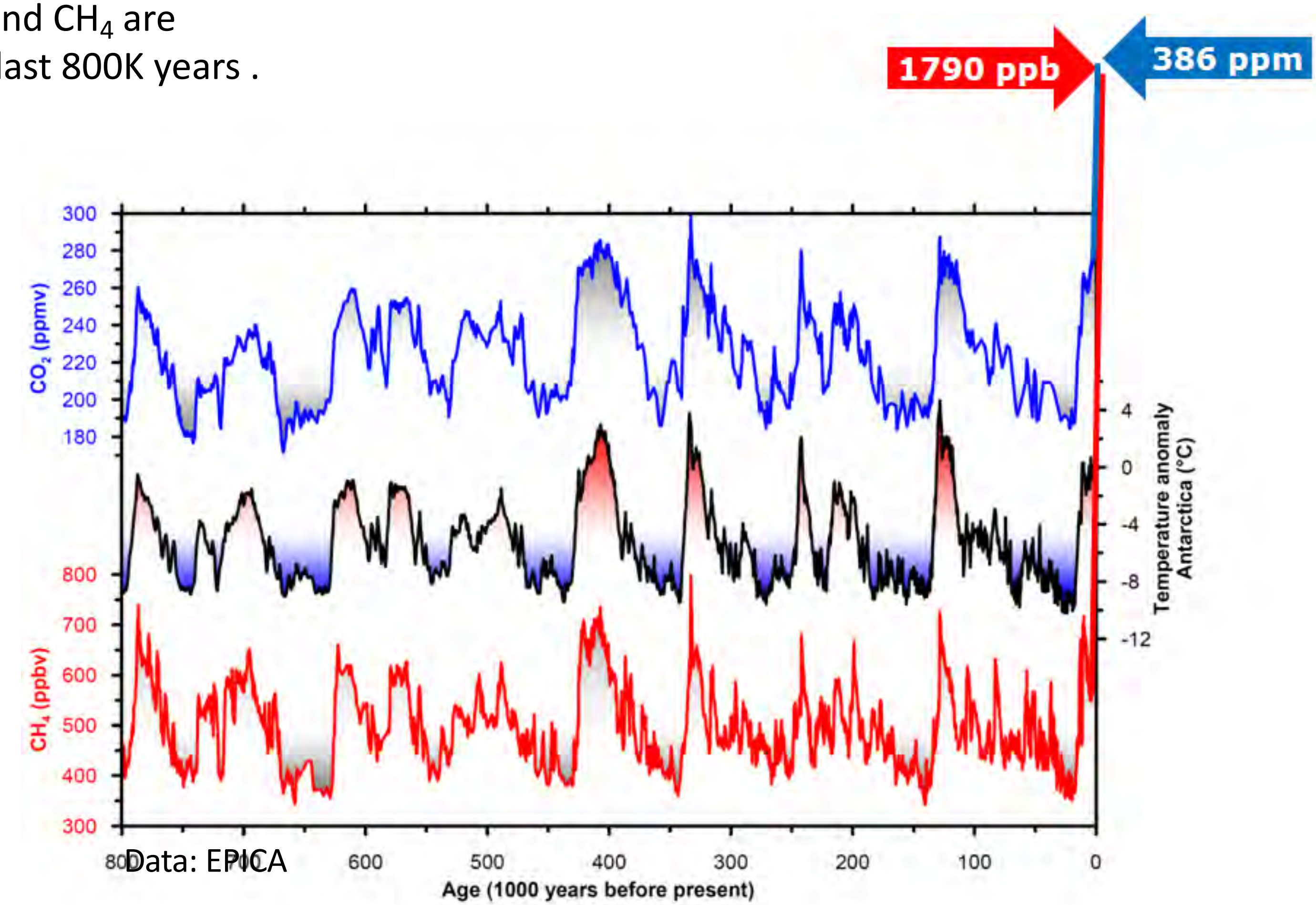


Figure 1.3: a) Carbon dioxide (CO_2) in parts per million (ppm). (b) Methane (CH_4) in parts per billion (ppb). [Figure source: Redrawn from NOAA-ESRL-GMD 2017.]

Key Finding 1: The Observed Increases in Atmospheric CO_2 and CH_4

Recent Increases in CO_2 and CH_4 are unprecedented over the last 800K years .



Data: EPICA

Key Finding 2: Anthropogenic Radiative Forcing

- The total anthropogenic radiative forcing in 2017 (not including anthropogenic aerosols) relative to 1750 was 3.1 W/m^2.
- CO_2 accounts for ~2.0 W/m^2.
- CH_4 accounts for ~0.5 W/m^2.
- Remainder is due to N_2O, CFCs and other Industrial GHGs.
- Global temperature, excluding short-term variability, now exceeds +1°C relative to the 1880-1920 mean in response to increased radiative forcing (Hansen et al., 2017).
- Emissions have **global** consequences, so we should not neglect to understand global GHG budgets.

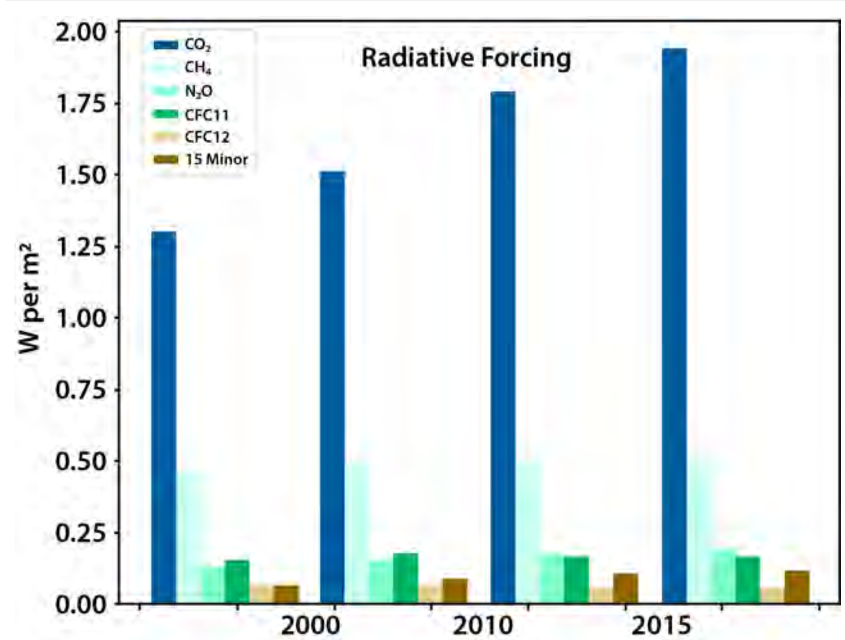


Figure 1.1: Major GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), trichlorofluoromethane (CFC11), and dichlorodifluoromethane (CFC12). The 15 minor GHGs include CFC-113; CCl_4; CH_3CCl_3; HCFCs 22, 141b, and 142b; HFCs 134a, 152a, 23, 143a, and 125; SF_6; and halons 1211, 1301, and 2402. Radiative forcing calculations, in watts (W) per m^2, are based on measurements of GHGs in air trapped in snow and ice in Antarctica and Greenland prior to about 1980 and atmospheric measurements taken since then. [Figure source: Redrawn from National Academies of Sciences, Engineering, and Medicine 2018.]

NOAA AGGI - based on atmospheric observations

The Global CO_2 Budget

- Geologic Carbon Cycle: $\tau \sim$ 100K years or more
- Fast Natural Carbon Cycle: $\tau \sim$ 1K years
- Fossil fuel use effectively speeds up the geologic carbon cycle by a factor of 100!

	1750–2011 Cumulative Pg C[c]	1980–1989 Pg C per Year	1990–1999 Pg C per Year	2000–2009 Pg C per Year	2007–2016 Pg C per Year	2016 Pg C per Year
Emissions						
Fossil Fuels and Industry	375 ± 30	5.5 ± 0.3	6.3 ± 0.3	7.8 ± 0.4	9.4 ± 0.5	9.9 ± 0.5
Land-Use Change	180 ± 80	1.2 ± 0.7	1.3 ± 0.7	1.2 ± 0.7	1.3 ± 0.7	1.3 ± 0.7
Partitioning to Carbon Reservoir						
Growth in Atmospheric CO_2[c]	240 ± 10	3.4 ± 0.1	3.1 ± 0.1	4.0 ± 0.1	4.7 ± 0.1	6.0 ± 0.2
Ocean Uptake	160 ± 80	1.7 ± 0.5	1.9 ± 0.5	2.1 ± 0.5	2.4 ± 0.5	2.6 ± 0.5
Land Uptake	155 ± 30	2.0 ± 0.6	2.5 ± 0.5	2.9 ± 0.8	3.0 ± 0.8	2.7 ± 0.9

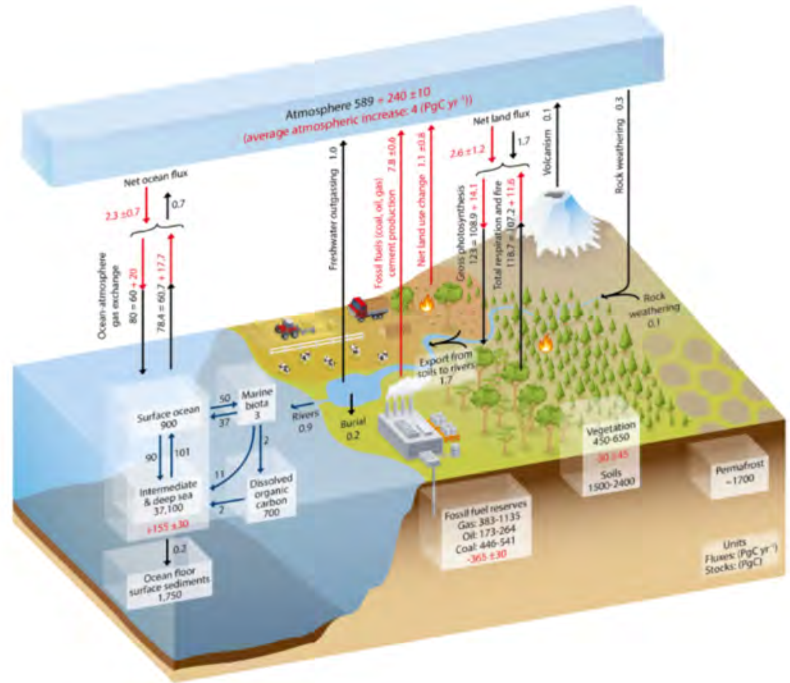


Figure 1.2: The boxed numbers represent reservoir mass or carbon stocks in petagrams of carbon (Pg C). Arrows represent annual exchange (fluxes) in Pg C per year. Black numbers and arrows represent preindustrial reservoir masses and fluxes, while red arrows and numbers show average annual anthropogenic fluxes for 2000 to 2009. The red numbers in the reservoirs denote cumulative changes of anthropogenic carbon for the industrial period Uncertainties are reported as 90% confidence intervals. [Figure source: Reprinted from Ciai et al., 2013, Figure 6.1. Copyright IPCC, used with permission.]

The Global CH_4 Budget

- The Global Methane Budget is uncertain, although net emissions and loss can be estimated from global observations.
- Unlike for CO_2, CH_4 has a rapid sink (mainly chemical destruction by reaction with OH) that approximately balances emissions.

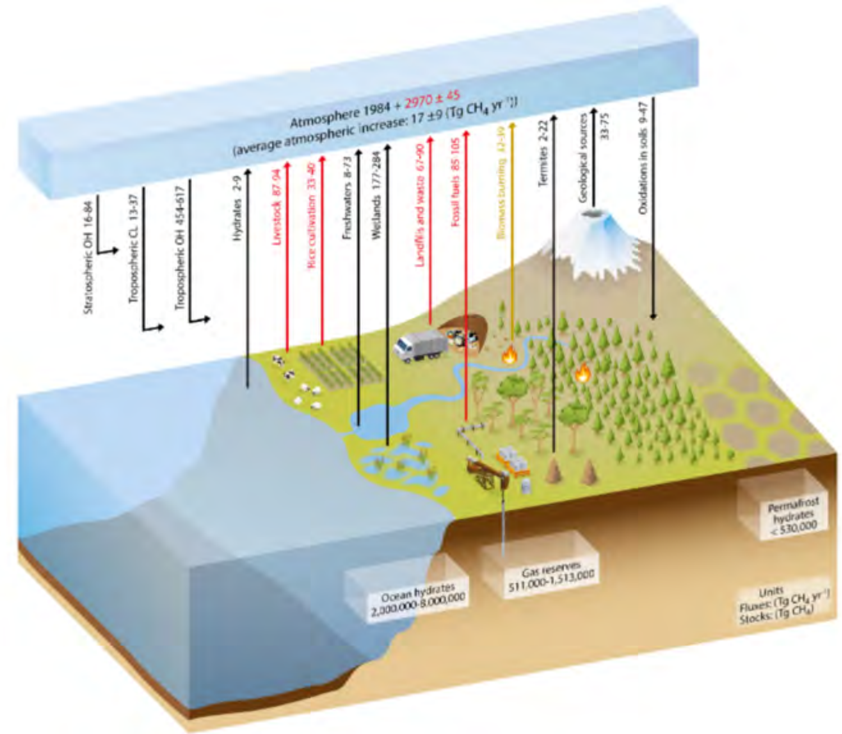


Figure 1.4: The arrows and boxed numbers represent annual fluxes in teragrams (Tg) of CH_4 per year estimated from 2000 to 2009 and CH_4 reservoirs in Tg CH_4. Reservoirs include the atmosphere and three geological reservoirs (i.e., hydrates on land and in the ocean floor and gas reserves). The black arrows show natural emissions, while red arrows show anthropogenic fluxes. The brown arrow represents total anthropogenic and natural emissions. [Figure source: Reprinted from Ciais et al., 2013, Figure 6.2. Copyright IPCC, used with permission.]

$$d[CH_4]/dt = \Sigma \text{Agriculture/Waste} + \Sigma \text{Natural} + \Sigma \text{Fossil Fuel Production} + \Sigma \text{Biomass Burning} - [CH_4]/\tau$$

The Global CH_4 Budget

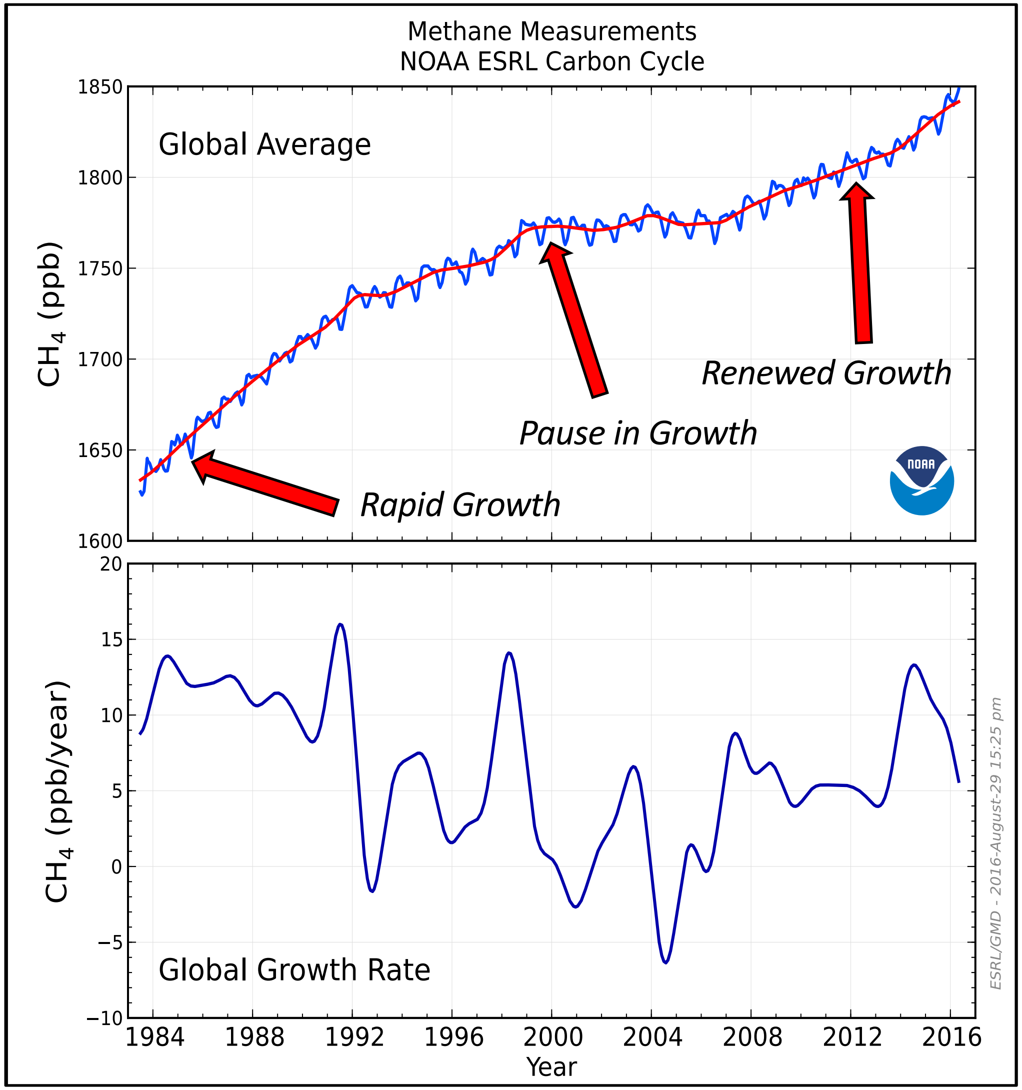
Rapid Growth/ Pause in Growth

1) Approach to Steady-State (1780 ppb by 2010s) Dlugokencky et al., 1998,2003

2) Decreases in O&G Emissions Since the 1980s (Aydin et al., 2011; Simpson et al., 2012)

3) Reductions in Rice Emissions (Kai et al., 2011)

4) Possibly due to changing chemical sink (mainly OH) Increased (Rigby et al., 2017)



The Global CH_4 Budget

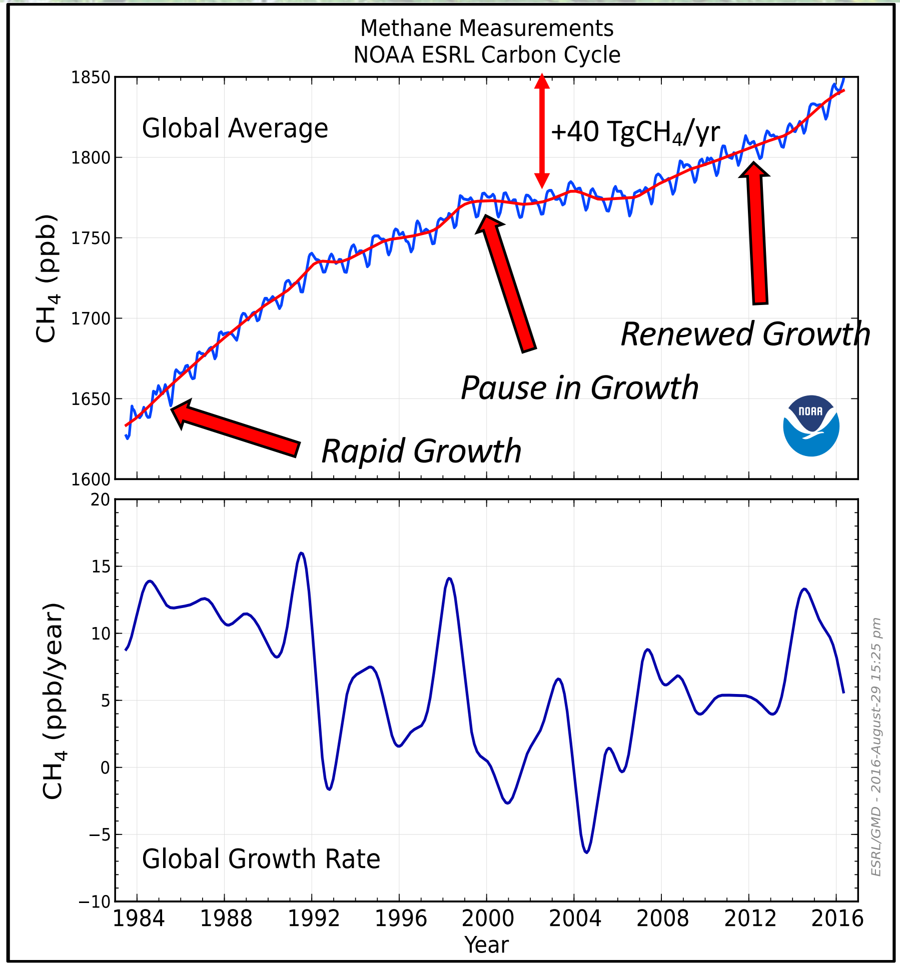
Renewed Growth: ***Likely Due Some Low Latitude Process***

1) Microbial Emissions Going Up based on methane isotope measurements (Nisbet et al., 2016, Schaefer et al., 2016, Schwietzke et al. 2016)

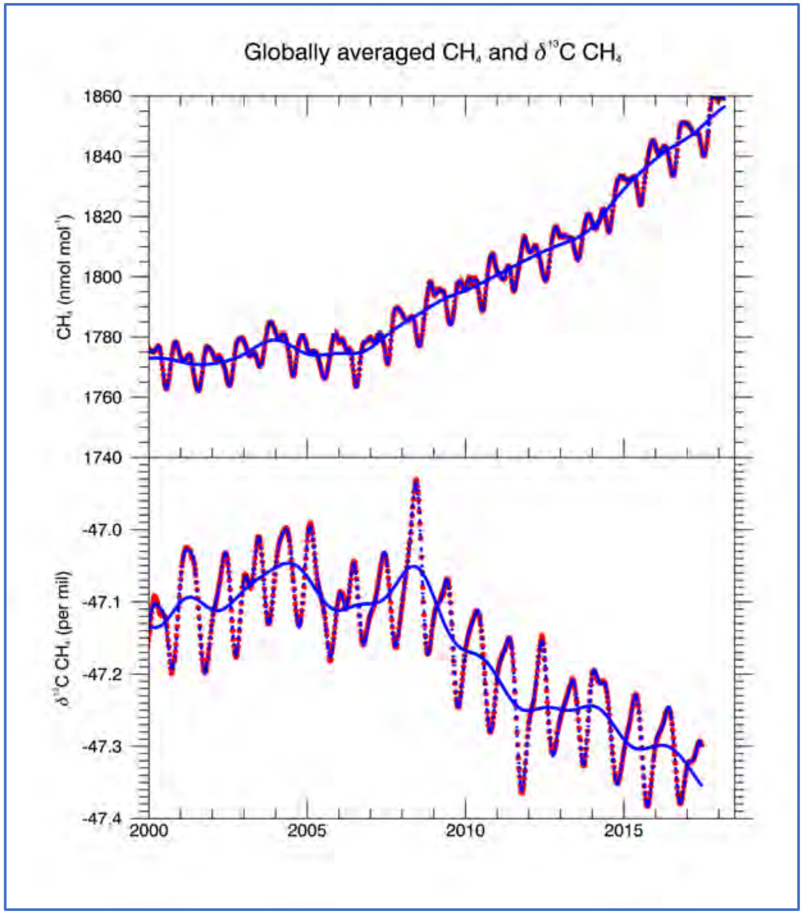
2) Could be Anthropogenic Microbial (Schaefer et al., 2016, Saunois et al., 2016).

3) Significant Contribution from fossil fuel emissions (Turner et al., 2016; Rice et al., 2016, Worden et al., 2017)

4) OH sink could have decreased (Rigby et al., 2017) but it may be hard to tell anything from isotopes (Turner et al., 2017). (Note that chemical models suggest constant OH).



The Global CH_4 Budget



$\delta^{13}C$-CH_4 : A Clear Indication that Microbial Sources are Behind the CH_4 Increase.

<u>Microbial sources</u>:

Anthropogenic: animals, rice agriculture, waste

Natural: wetlands, insects, animals

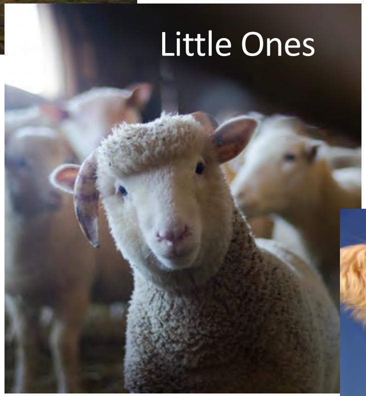
Data: S. Michel, INSTAAR

The Global CH_4 Budget

CH_4 From Animals

Global	Population Change 2006-2016 (+/- 10-20%)	Emission per Animal	Change in Emissions*
Big Ones	116 M	50-100 kg/yr	7.7 Tg/yr
Little Ones	238 M	5-8 kg/yr	1.3 Tg/yr

(Another 0.6 Tg/yr for manure)



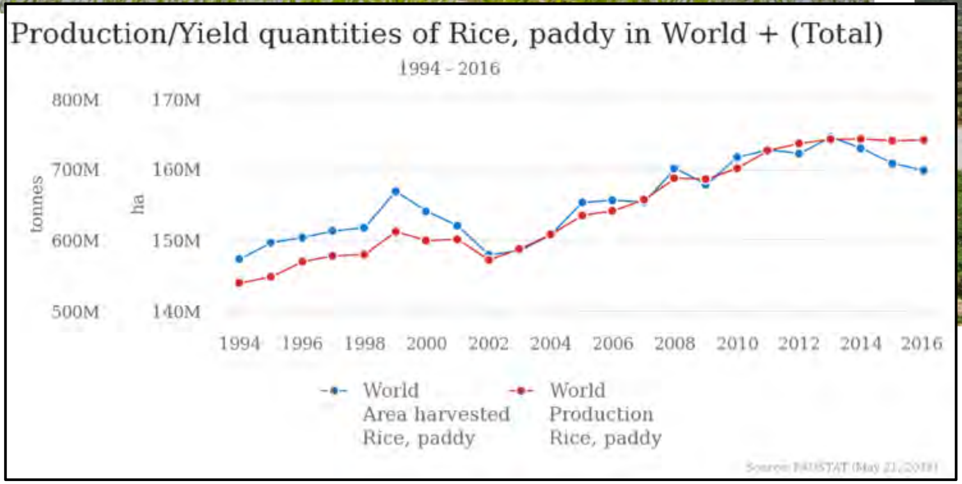
Goats:	5 kg/yr
Sheep:	8 kg/yr
Dairy Cattle:	110 kg/yr
Non-Dairy Cattle:	50 kg/yr

* Population growth of animal types in each category taken into account

The Global CH_4 Budget

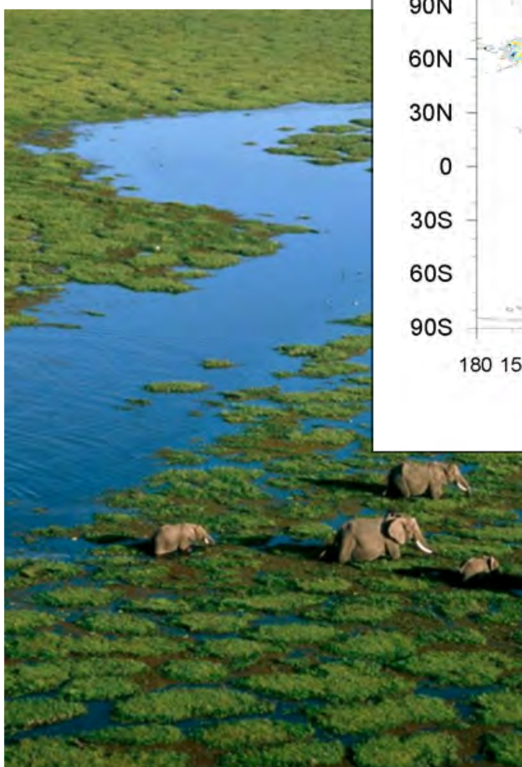
Rice Agriculture

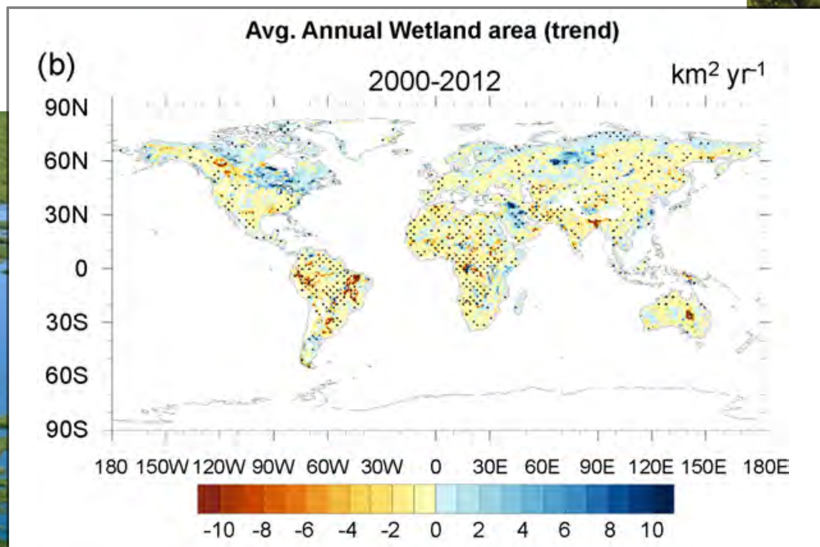
From 2006-2016, growth in CH_4 Emissions from rice agriculture are likely to have been small: < 0.8-1.4 $TgCH_4$/yr



The Global CH_4 Budget

Wetlands



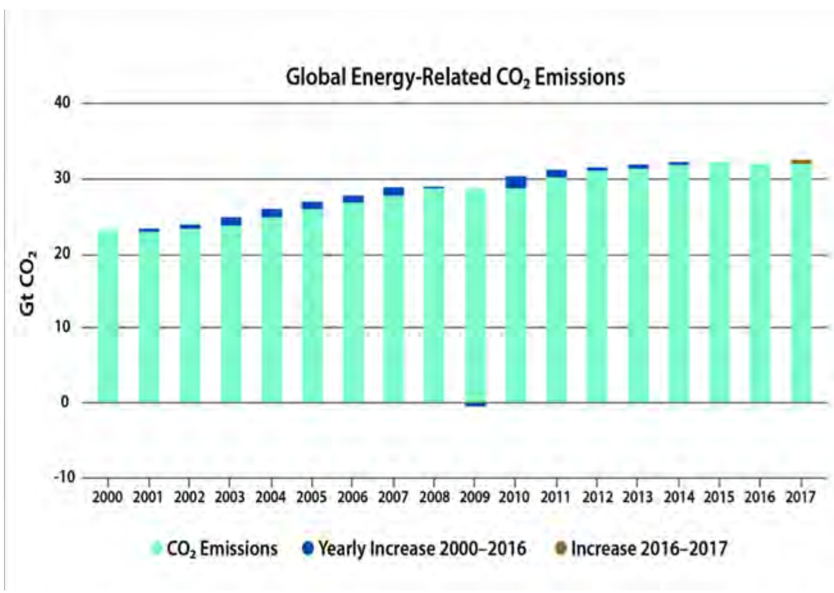


Poulter et al., 2017: Global wetland emissions constant over 2002-2012, with small decreases in the Tropics (~1 Tg/yr).

But the SWAMPS-GLWD dataset used for wetland areas may underestimate actual wetland variability.

Key Finding 3: Changes in Global Fossil Emissions

- Global Energy Demand Increased by 2.1% in 2017.
- 40% of this was driven by China and India.
- 72% of this rise was met by fossil fuels.
- There were declines in CO_2 emissions from some countries, such as the US, due to more use of renewables.



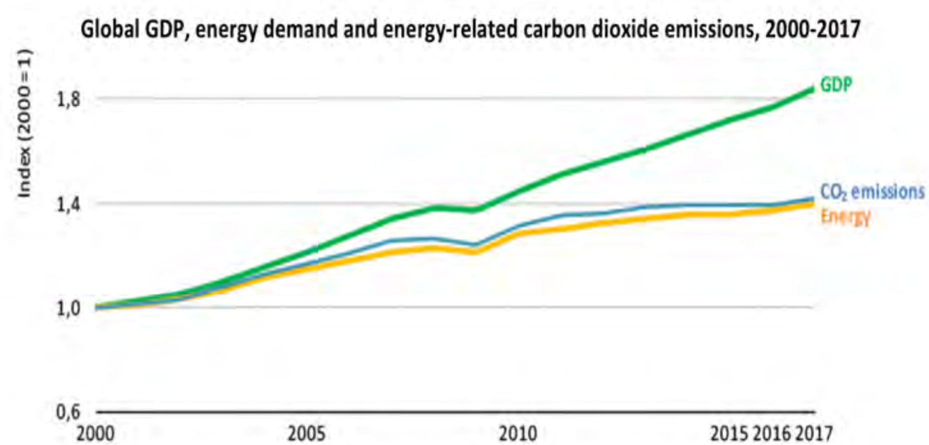
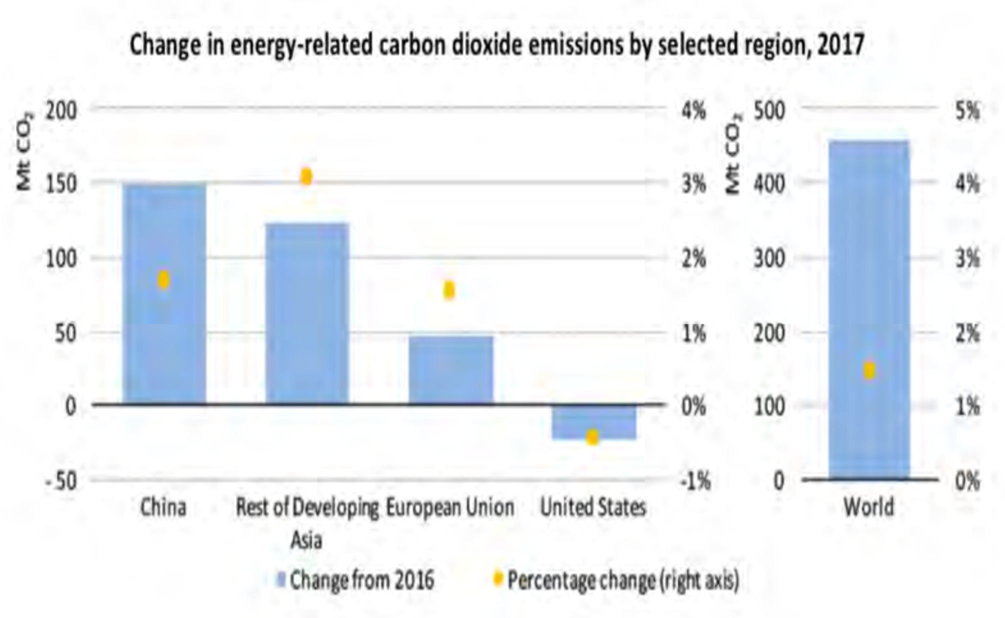


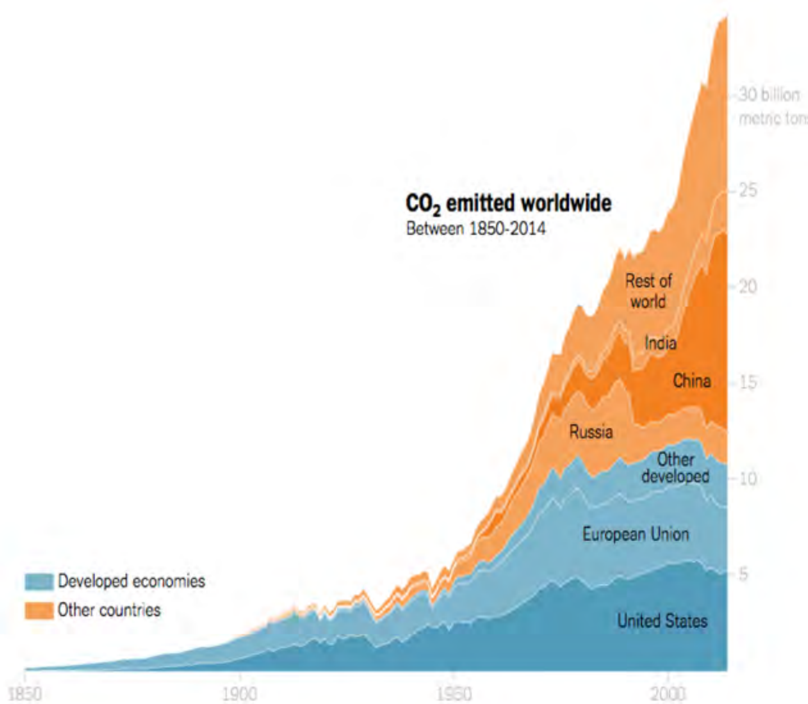
Figure 1.5: **(a)** Fossil fuel CO_2 emissions in gigatons (Gt) and their yearly increase. **(b)** Growth in CO_2 emissions, energy demand, and global gross domestic product (GDP) normalized to 2000. [Figure source: Redrawn from International Energy Agency (IEA) data in the *Global Energy & CO_2 Status Report 2017* (IEA 2017). Copyright Organisation for Economic Cooperation and Development/ IEA, used with permission.]

Key Finding 3: Changes in Global Fossil Emissions

China is now the world's top emitter, approximately doubling annual US emissions.



Source: EIA



NYTimes, June 1, 2017, data: CDIAC, Oak Ridge, TN

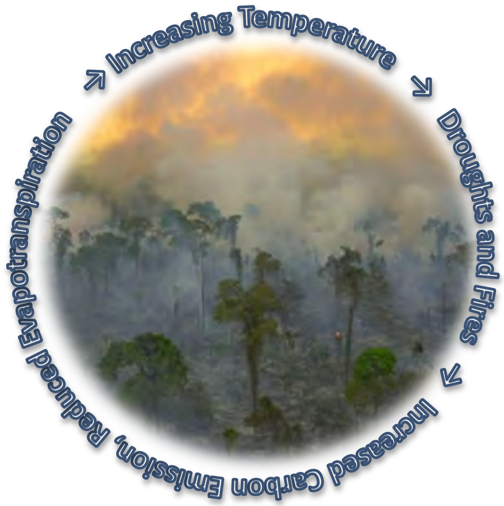
Key Finding 5: How Much More Carbon Can we Emit? (And stay below 2°C)

- Some studies suggest it's too late (Mauritsen and Pincus 2017; Raftery et al., 2017).
- The temperature response to CO_2 emissions is estimated at +0.7 to +2.4 C per 1,000 Pg C_{eq} (based on observations and models).
- To have a 67% chance of limiting warming to 2°C, cumulative emissions need to stay under ~1000 Pg C_{eq}.
- 779 Pg C_{eq} has already been emitted, leaving only another 221 Pg C_{eq}.
- Global emissions are now ~11 Pg C year, so this limit may be reached in ~20 years.
- We may have longer if we accept more risk (e.g. 33% chance => 80 years)
- This estimate does not include carbon cycle-climate feedbacks though.

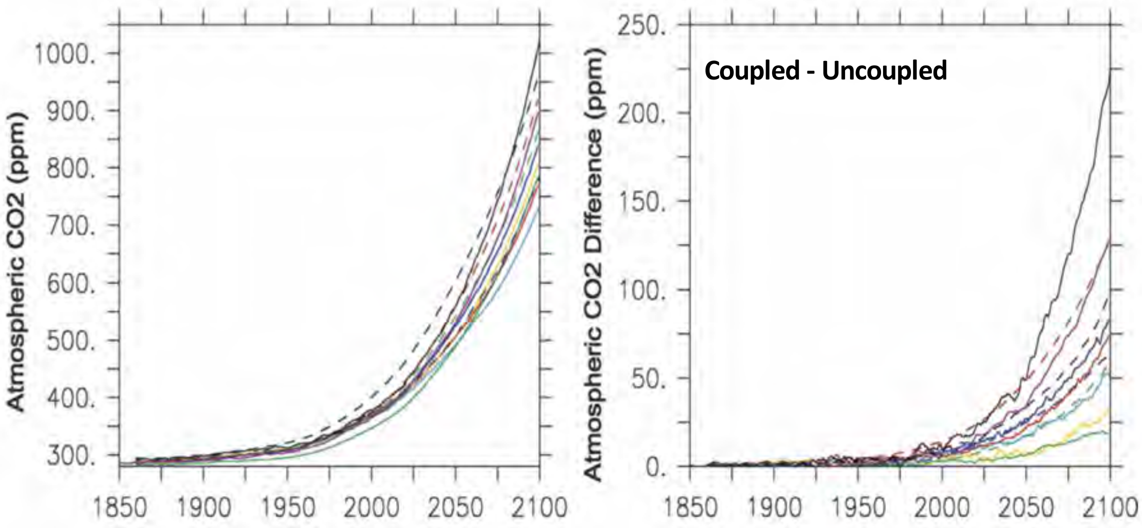
Carbon Cycle – Climate Feedbacks

Climate Feedbacks:

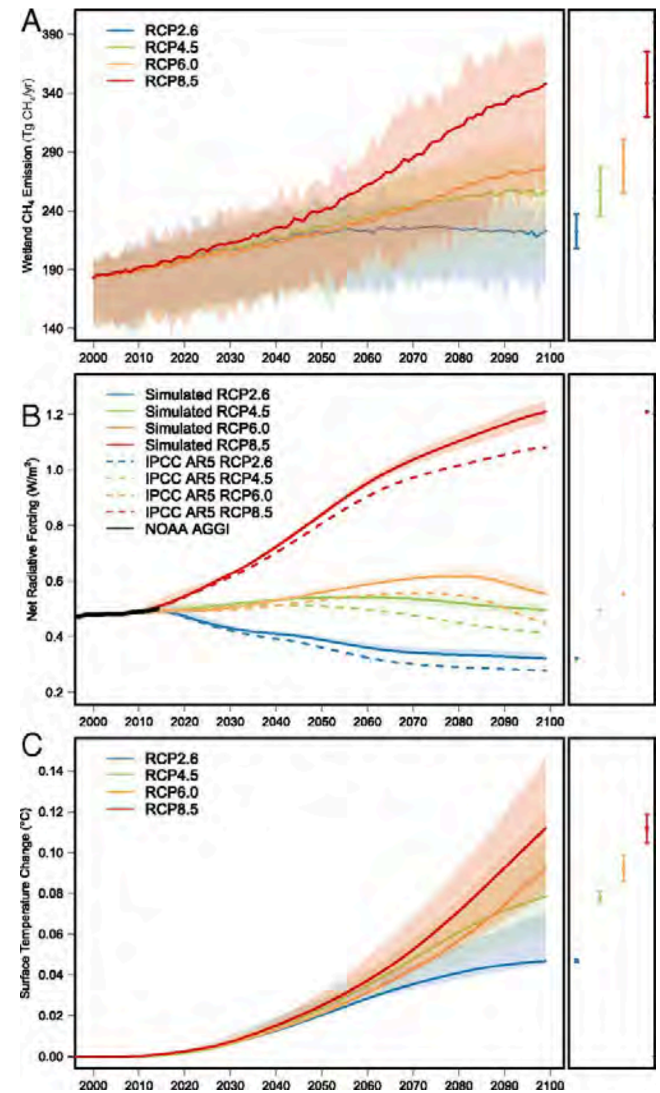
1) Are they underway?
2) Can we detect them?
3) Can we predict them accurately?



Carbon Cycle – Climate Feedbacks



Friedlingstein et al., *J. Clim.*, 2006 (C4MIP)
(Similar Conclusions in Friedlingstein et al., 2014 (CMIP5))



Zhang et al., PNAS, 2017

Carbon Cycle Feedbacks are Uncertain

Key Findings From SOCCR2, Chapter 1

1. CO_2 has increased from a preindustrial abundance of 280 parts per million (ppm) of dry air to over 400 ppm since 2014—an increase of 43%. Methane (CH_4) has increased from a preindustrial abundance about 700 parts per billion (ppb) of dry air to more than 1,850 ppb as of 2017—an increase of over 2.5 times. The current understanding of the sources and sinks of atmospheric carbon supports the dominant role of human activities, especially fossil fuel combustion, in the rapid rise of atmospheric carbon. [Very high confidence]

2. The total global anthropogenic radiative forcing resulting from major anthropogenic greenhouse gases (GHGs, not including anthropogenic aerosols) relative to the year 1750 was 3.1 watts per meter squared (W/m^2) in 2017. Carbon dioxide accounted for 2 W/m^2, and CH_4 accounted for 0.5 W/m^2. The global temperature in 2017 relative to the 1880-1920 average is greater than +1.0 °C in response to this increased radiative forcing (Hansen et al. 2017). [Very high confidence]

3. Global fossil fuel emissions of CO_2 increased at a rate of about 4% per year from 2000 until 2013, when the rate of increase declined to about 2% per year. Global emissions may have become slightly more uncoupled from economic growth, due to greater efficiency and more reliance on less carbon intensive natural gas and renewable energy sources. Emissions were flat in 2015 and 2016, but increased again in 2017 by an estimated 2.0%.

4. Net CO_2 uptake by lands and oceans removes about half of annually emitted CO_2 from the atmosphere, which helps keep concentrations much lower than would be expected if all emitted CO_2 remained in the atmosphere. The magnitude of future land and ocean carbon sinks is uncertain because the responses of the carbon cycle to future changes in climate are uncertain. [High confidence]

5. Only ~221 Pg C equivalent can be emitted from 2017 forward to stay below 2 ˚ C warming. This limit could be reached in as little as 20 years. This estimate is uncertain due to carbon cycle–climate feedbacks. [Medium confidence]