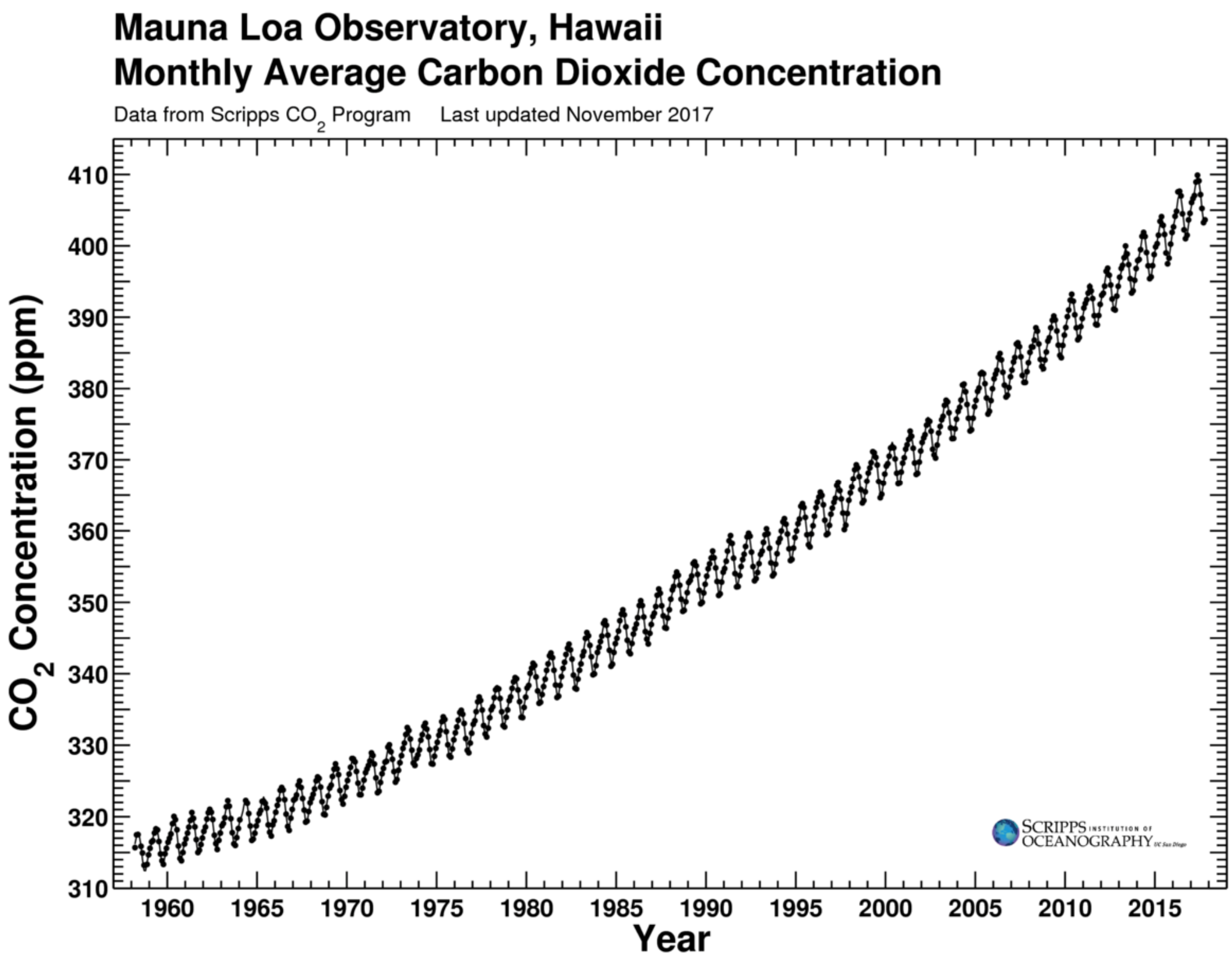
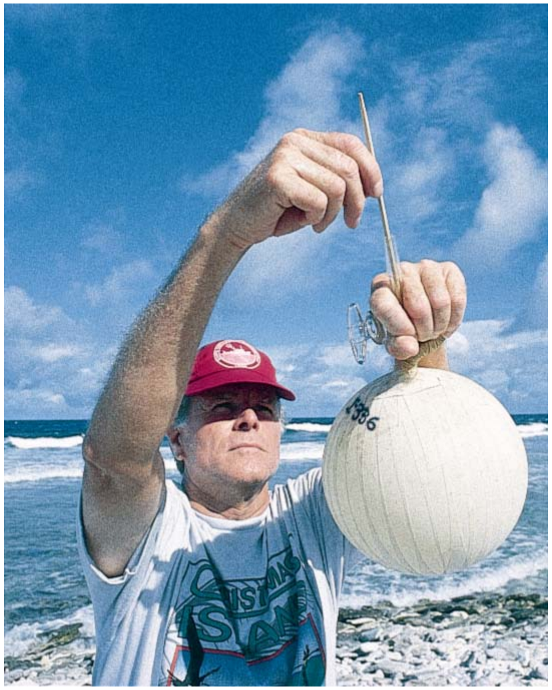
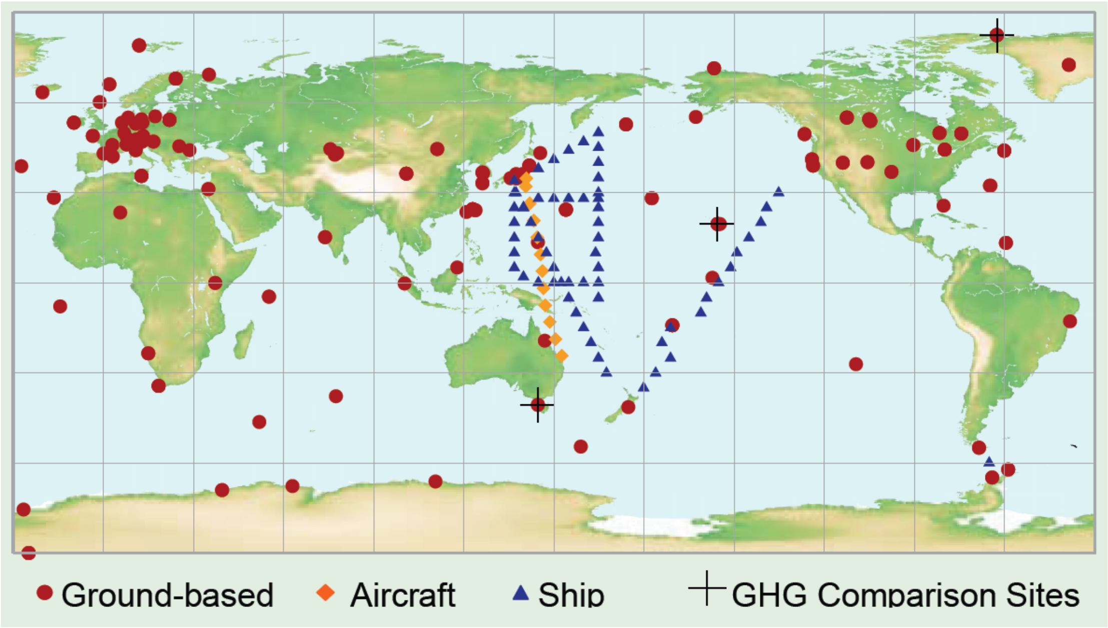
The global carbon cycle

Heather Graven



Atmospheric measurements are conducted all over the world



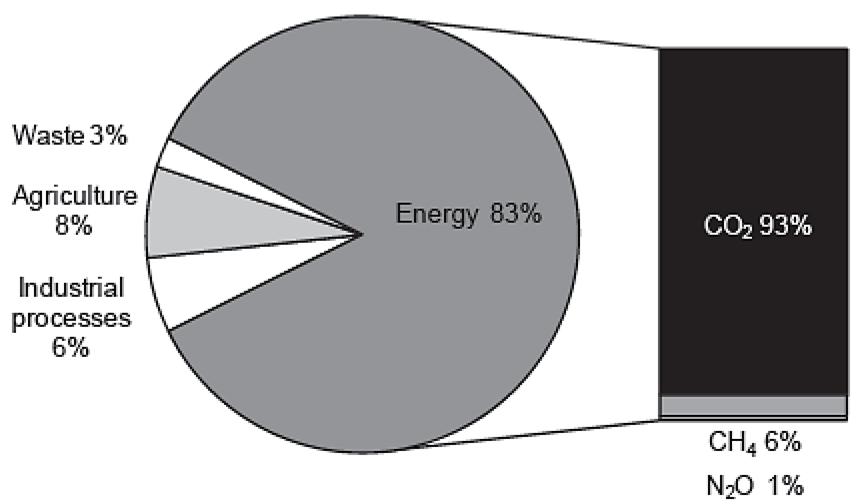


Images courtesy SIO, NSF, NASA, NERC

GHG emissions have been growing rapidly

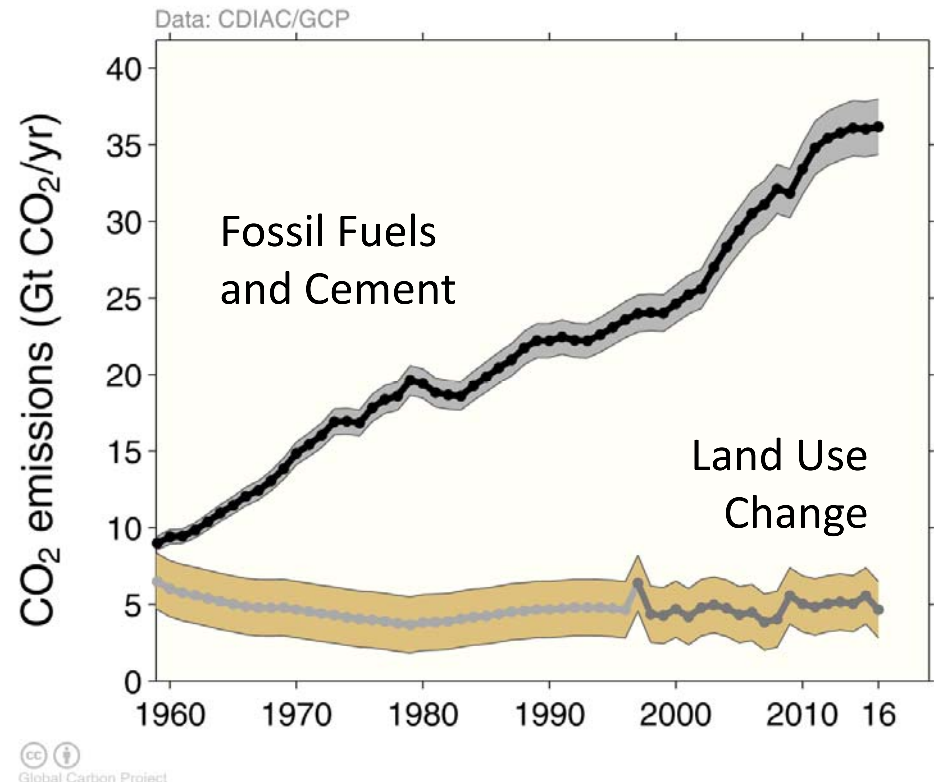
CO_2 emissions from fossil fuel combustion for energy are the largest source of GHGs by far

Anthropogenic GHG Emissions



* Based on Annex I data for 2011; without Land Use, Land-Use Change and Forestry, and with Solvent Use included in Industrial Processes and "other" included with waste.

Source: UNFCCC.



Units

1 Gigatonne (Gt) = 1 billion tonnes = 1×10^{15} g

1 ppm CO_2 = 7.8 Gt CO_2 = 2.1 Gt C

Examples

Emissions from burning 1 litre of petrol: 2.3 kg CO_2

Mass of a car: 1000 kg = 1 tonne

Global per capita fossil fuel emissions in 2013: 5 tonnes CO_2 per person

UK per capita household waste in 2012-13: 420 kg per person

Our energy system is heavily reliant on fossil fuels

Renewables like solar and wind energy have been growing rapidly but they are still a tiny fraction of total energy supply

Figure 1: 2014 fuel shares in world total primary energy supply

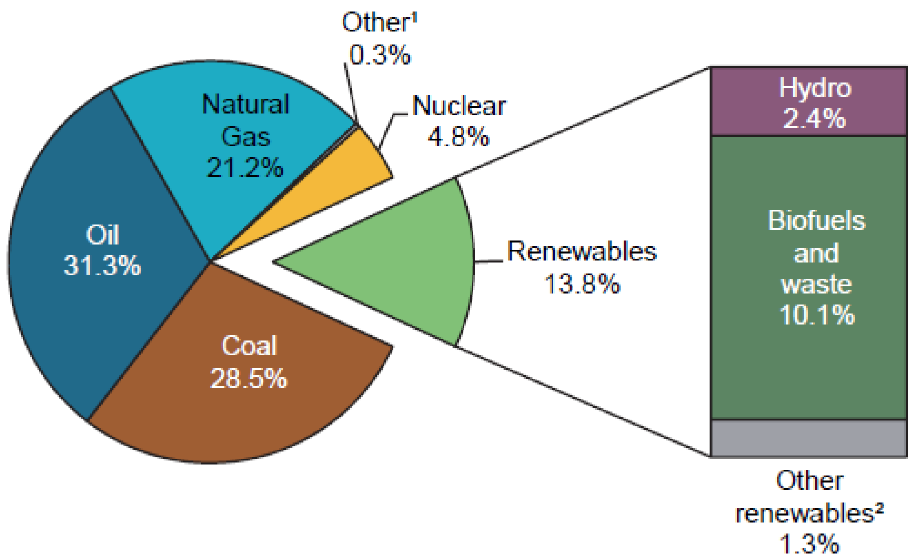
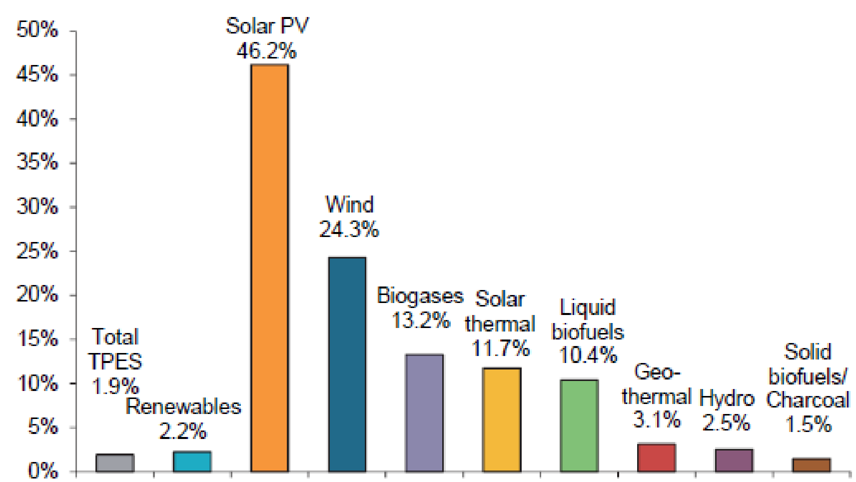
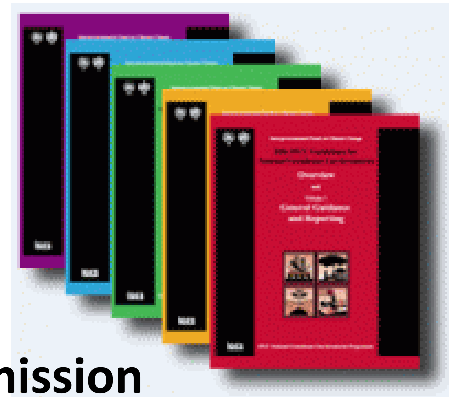


Figure 3: Annual growth rates of world renewables supply from 1990 to 2014



IEA Renewables Information (2016 edition)

Estimates of fossil fuel CO_2 emissions are based on accounting of activities according to e.g. IPCC guidelines



Emissions = Activity Data x Emission Factor

$$CI = \frac{\text{Carbon Content (g C / g fuel)} \times \text{Combustion Efficiency (\%)} \times \frac{44\ \text{g}\ CO_2}{12\ \text{g C}}}{\text{Energy Density (kWh / g fuel)}}$$

Full life-cycle Carbon Intensity also depends on mining, transport, transmission, other GHGs, etc

Indicative Carbon Intensity by Fuel

Fuel	$gCO_2\ kWh^{-1}$
Coal*	800 - 1000
Peat	740
Petrol / Diesel / Fuel Oil	700
Kerosene	640
Natural Gas*	400

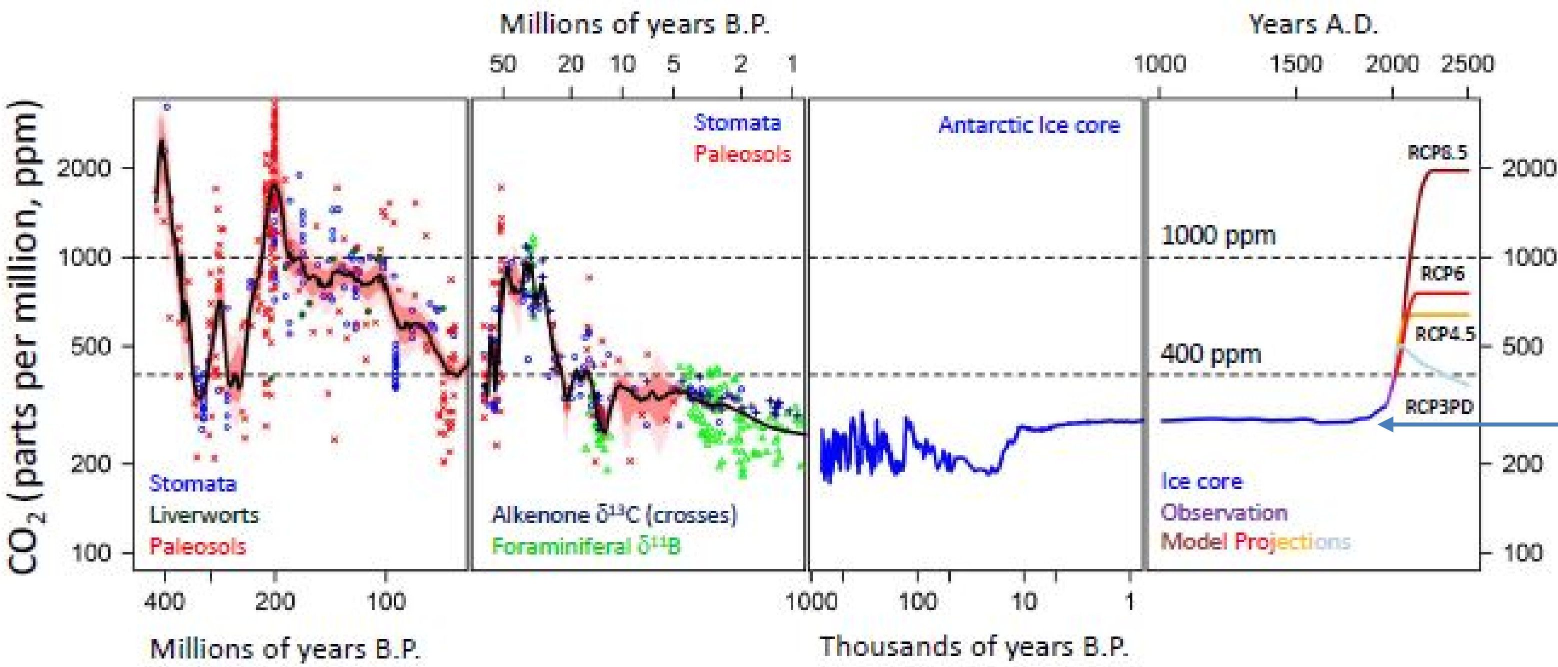
* Main fossil fuels used for electricity

Carbon Intensity of electricity by country, 2009-11

Country	$gCO_2\ kWh^{-1}$
China	780
US	500
UK	450
France	70
Norway	10

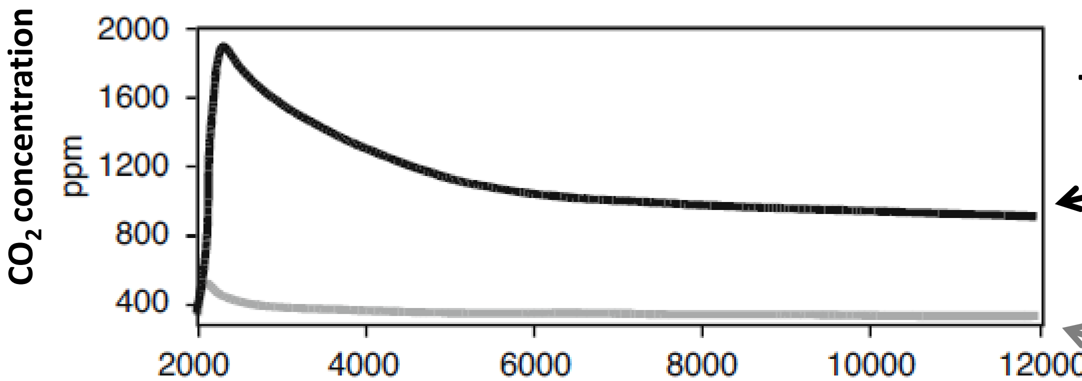
IEA, 2013

Atmospheric CO_2 concentration has varied over Earth's history



Preindustrial concentration: 288 ppm CO_2

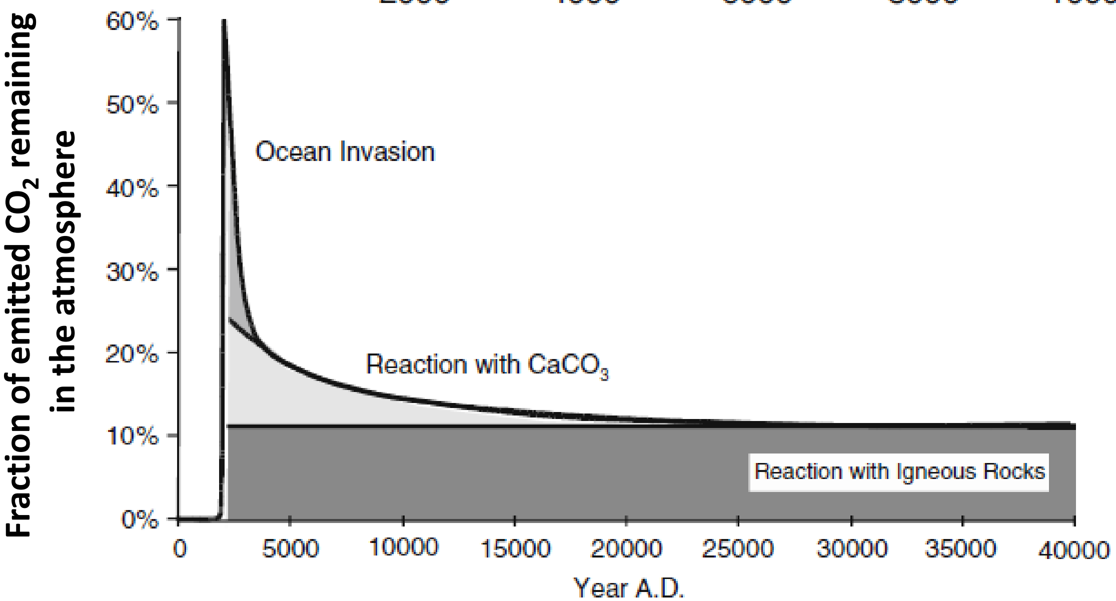
Atmospheric CO_2 remains elevated for millennia because some removal processes are slow



Total emissions:

18300 Gt CO_2 ("business-as-usual")

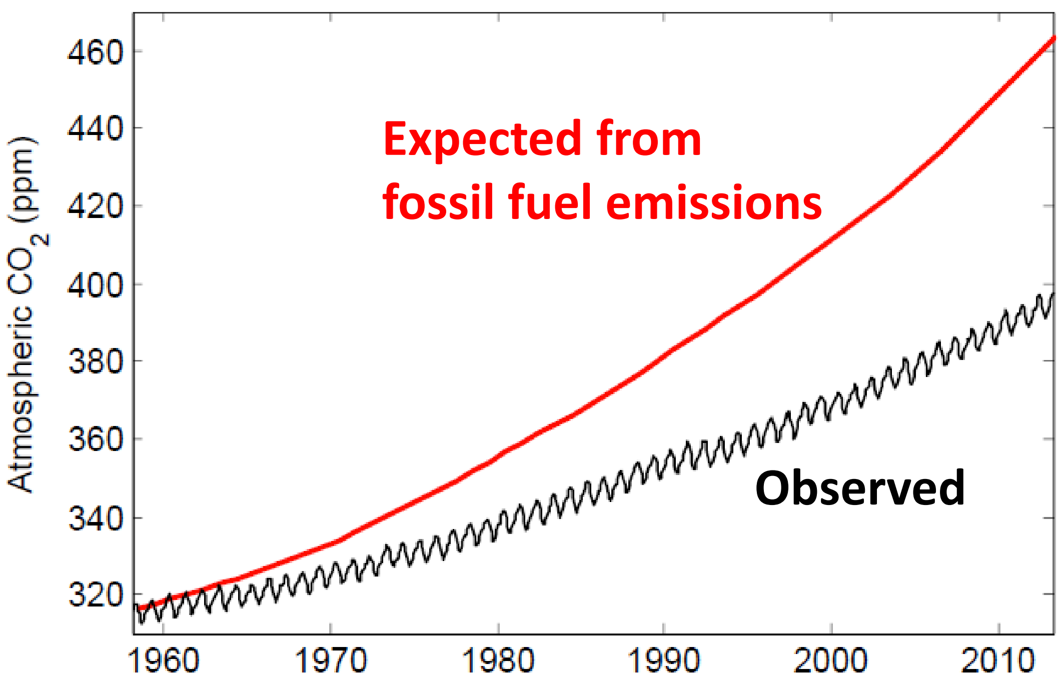
3700 Gt CO_2 (current mitigation target)

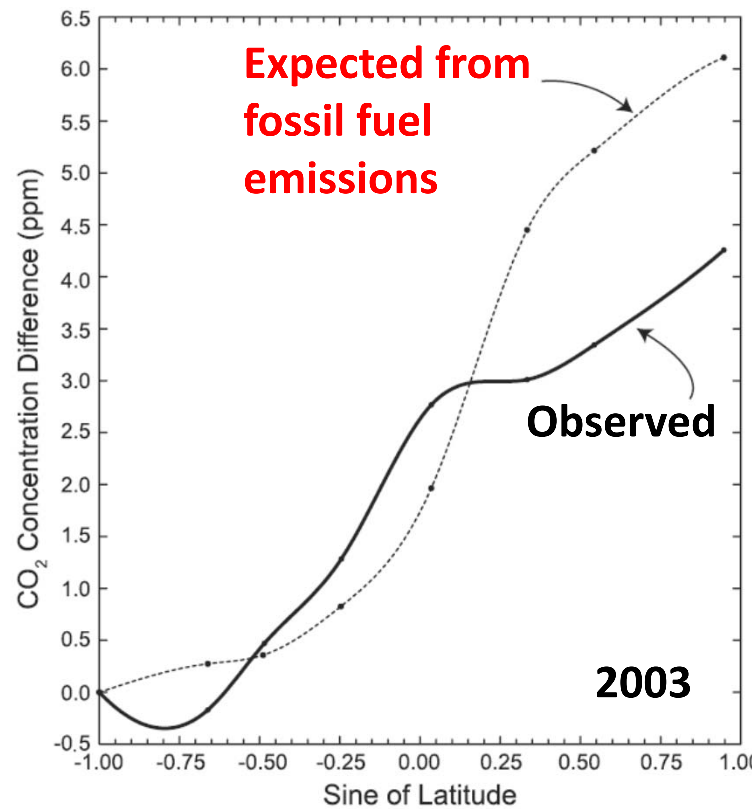


Archer and Brovkin 2008

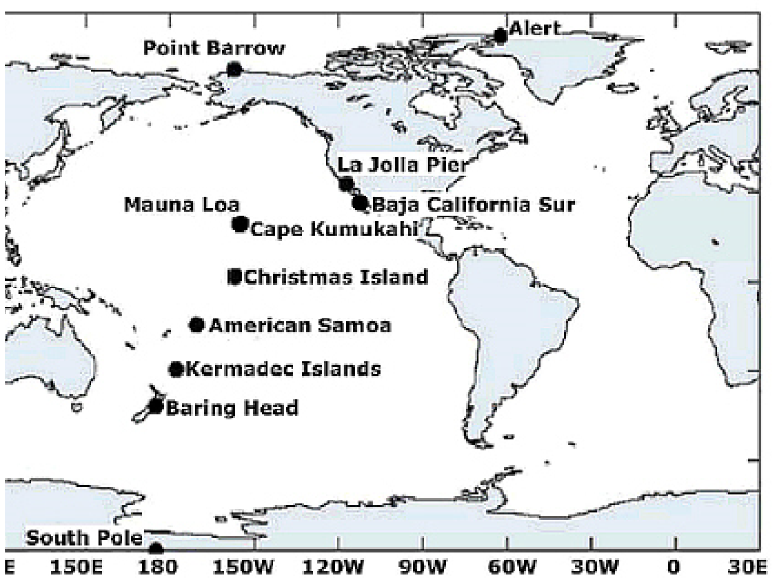
Atmospheric CO_2 integrates sources and sinks

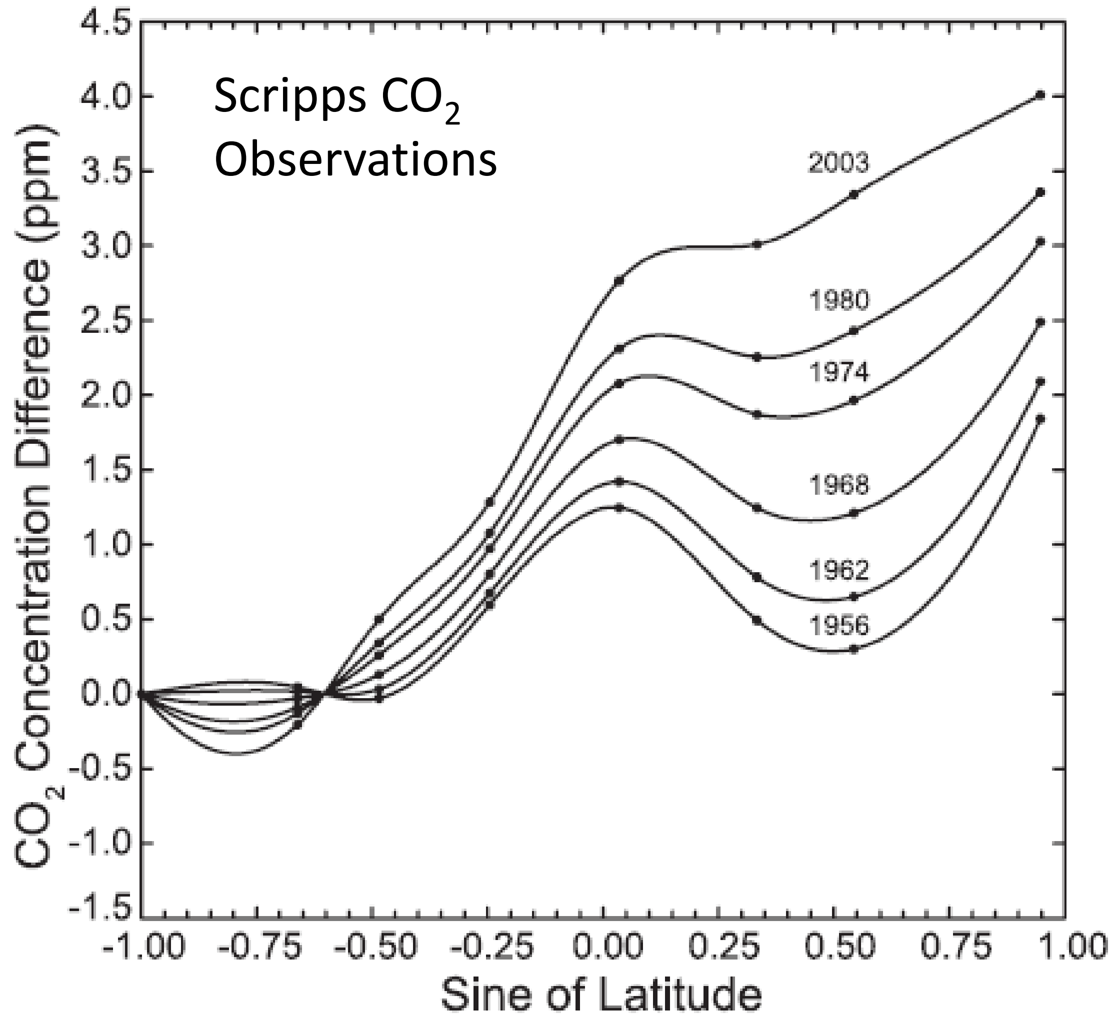
Interhemispheric gradient of atmospheric CO_2 is less than expected from emissions due to net CO_2 uptake by the oceans and by land plants in the Northern Hemisphere





The spatial distribution of CO_2 is evolving due to CO_2 sources and sinks

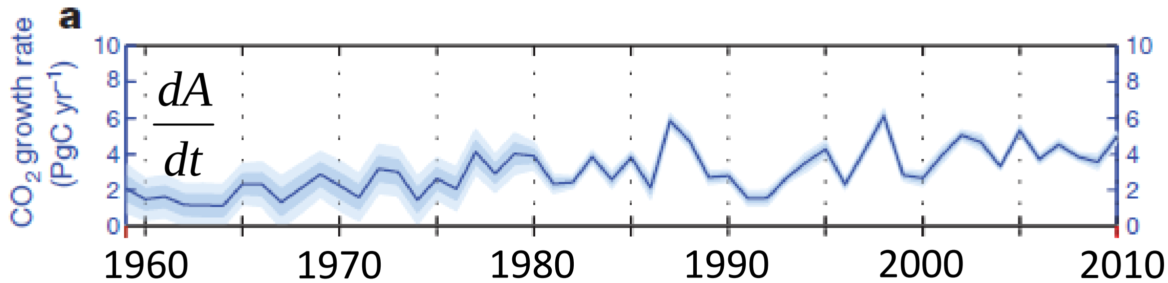




Keeling et al. 2011

Atmospheric CO_2 integrates net sources and sinks

$$\frac{dA}{dt} = F + L - O - B$$



Ballantyne et al. 2012

Atmospheric CO_2 integrates net sources and sinks

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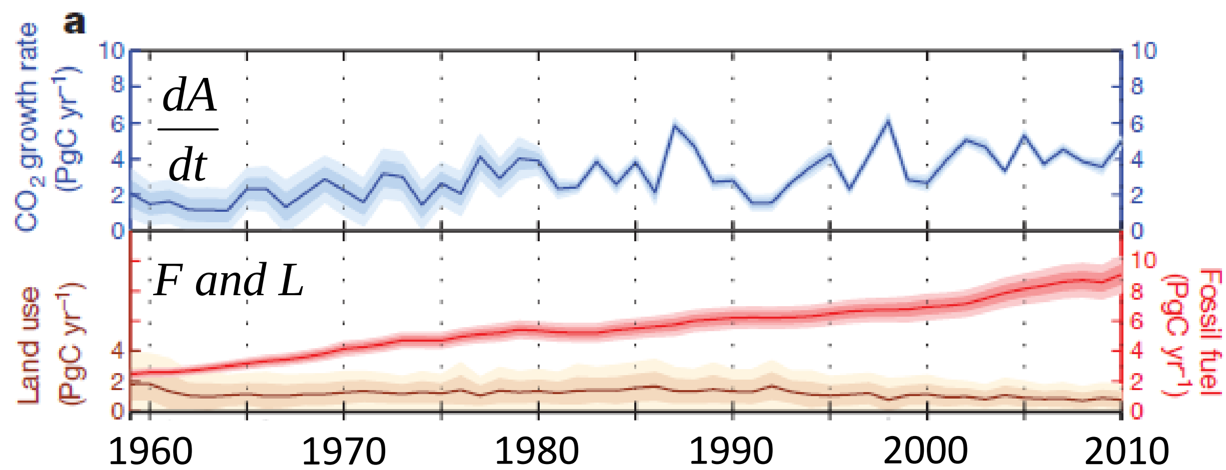


Airborne fraction: 45%

Ballantyne et al. 2012

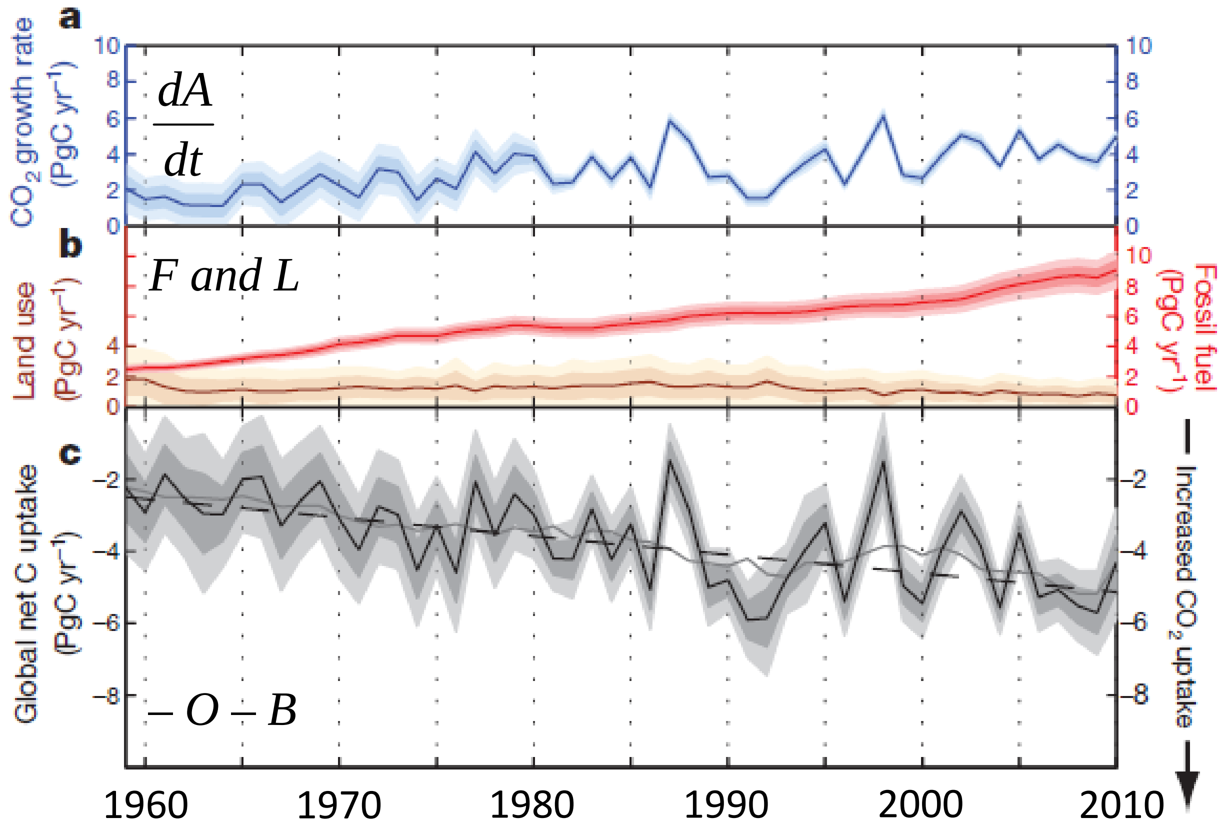
Atmospheric CO_2 integrates net sources and sinks

$$\frac{dA}{dt} = F + L - O - B$$

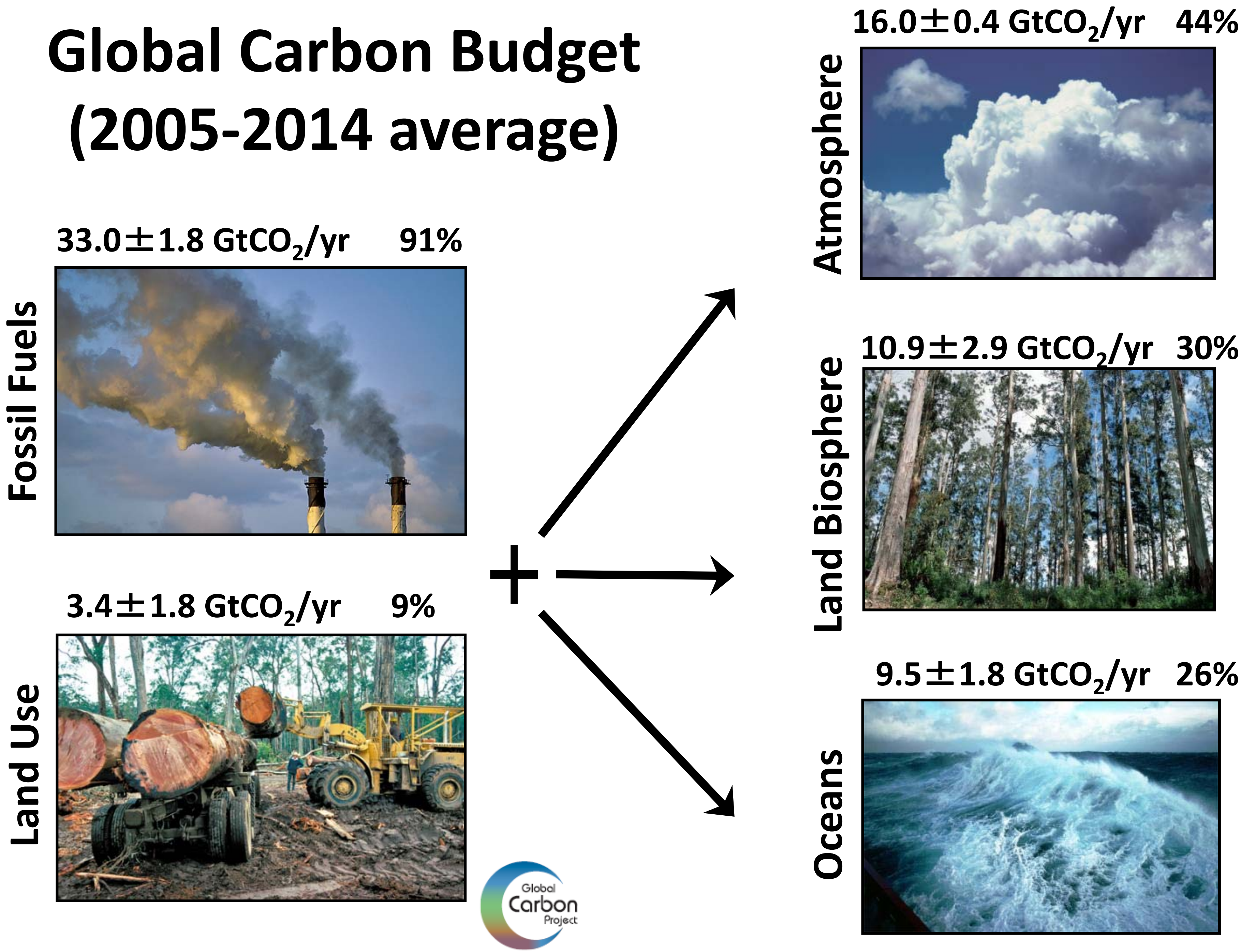
Sinks of CO_2 in the land and ocean have been growing consistently with emissions

Airborne fraction: 45%

Total uptake 5.0 ± 0.9 PgC/yr in 2012, doubled since 1960



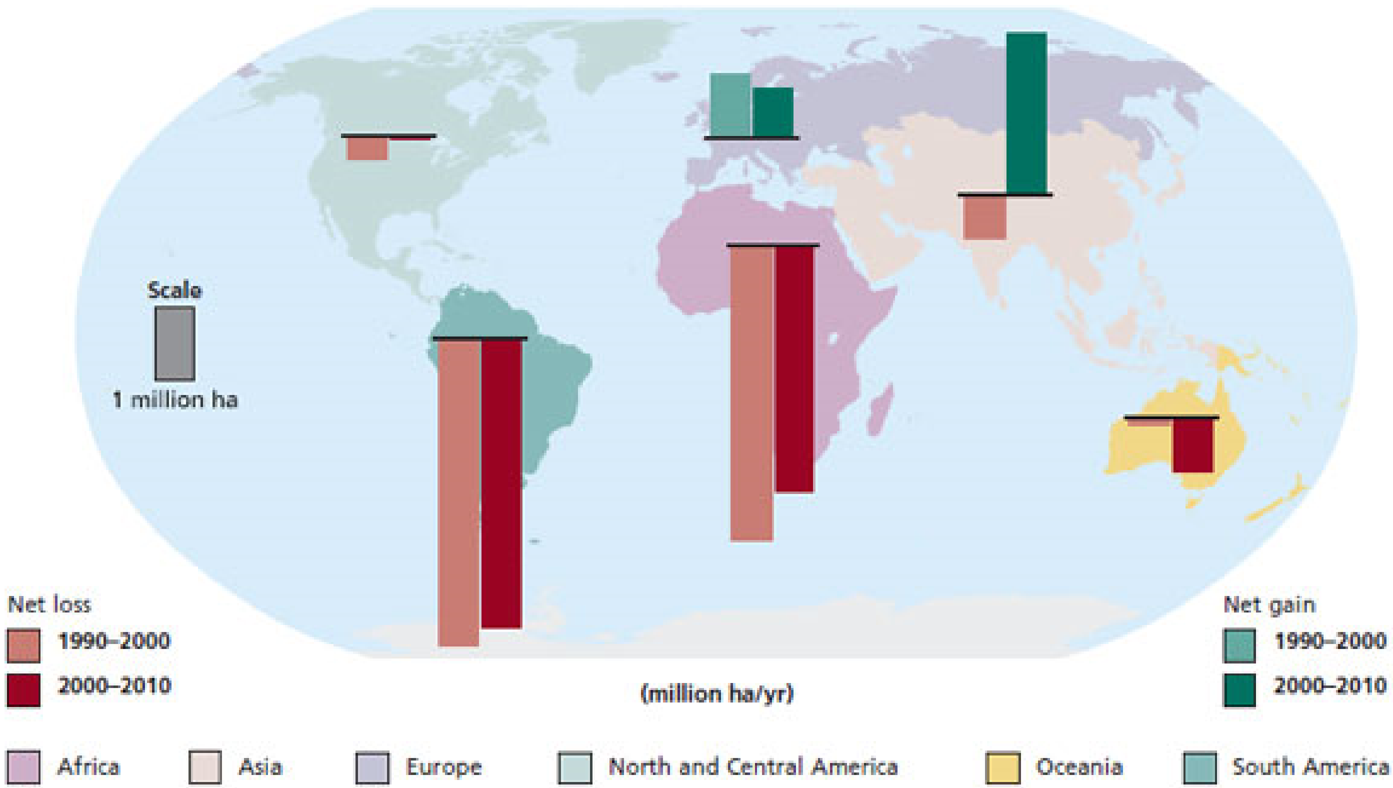
Ballantyne et al. 2012



Global Carbon Budget
(2005-2014 average)
33.0±1.8 $GtCO_2$/yr 91%
Fossil Fuels
3.4±1.8 $GtCO_2$/yr 9%
Land Use
+
16.0±0.4 $GtCO_2$/yr 44%
Atmosphere
10.9±2.9 $GtCO_2$/yr 30%
Land Biosphere
9.5±1.8 $GtCO_2$/yr 26%
Oceans
Global Carbon Project

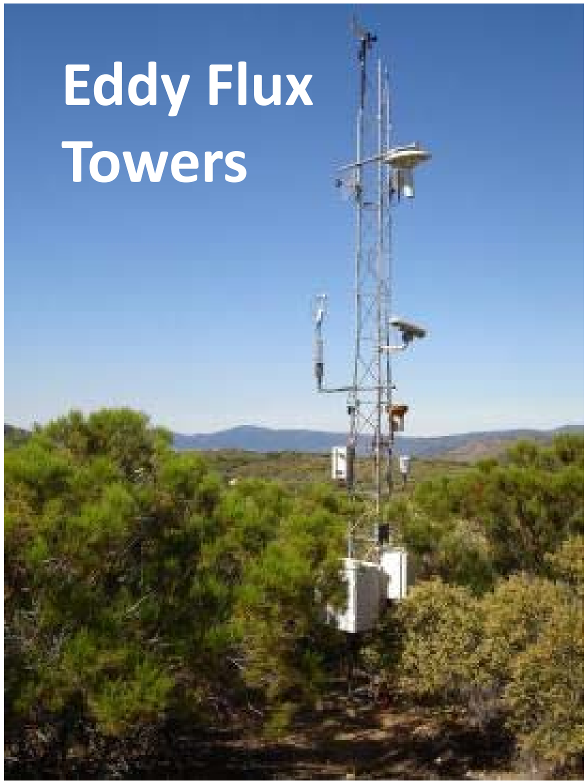
Land use is dominated by tropical deforestation emissions, but net uptake in some places

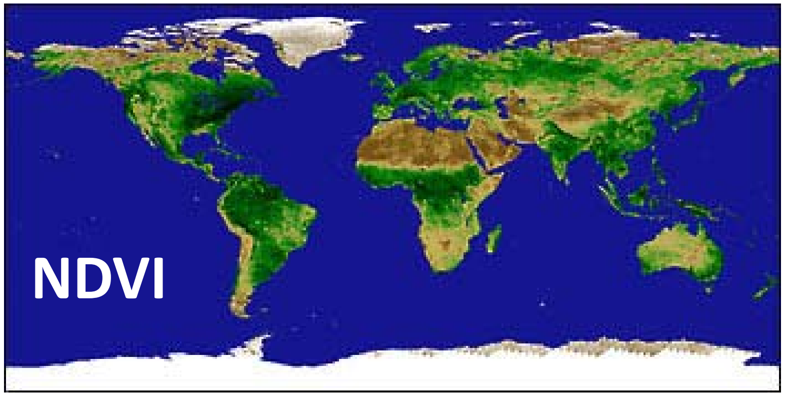
FIGURE 4
Annual change in forest area by region, 1990–2010



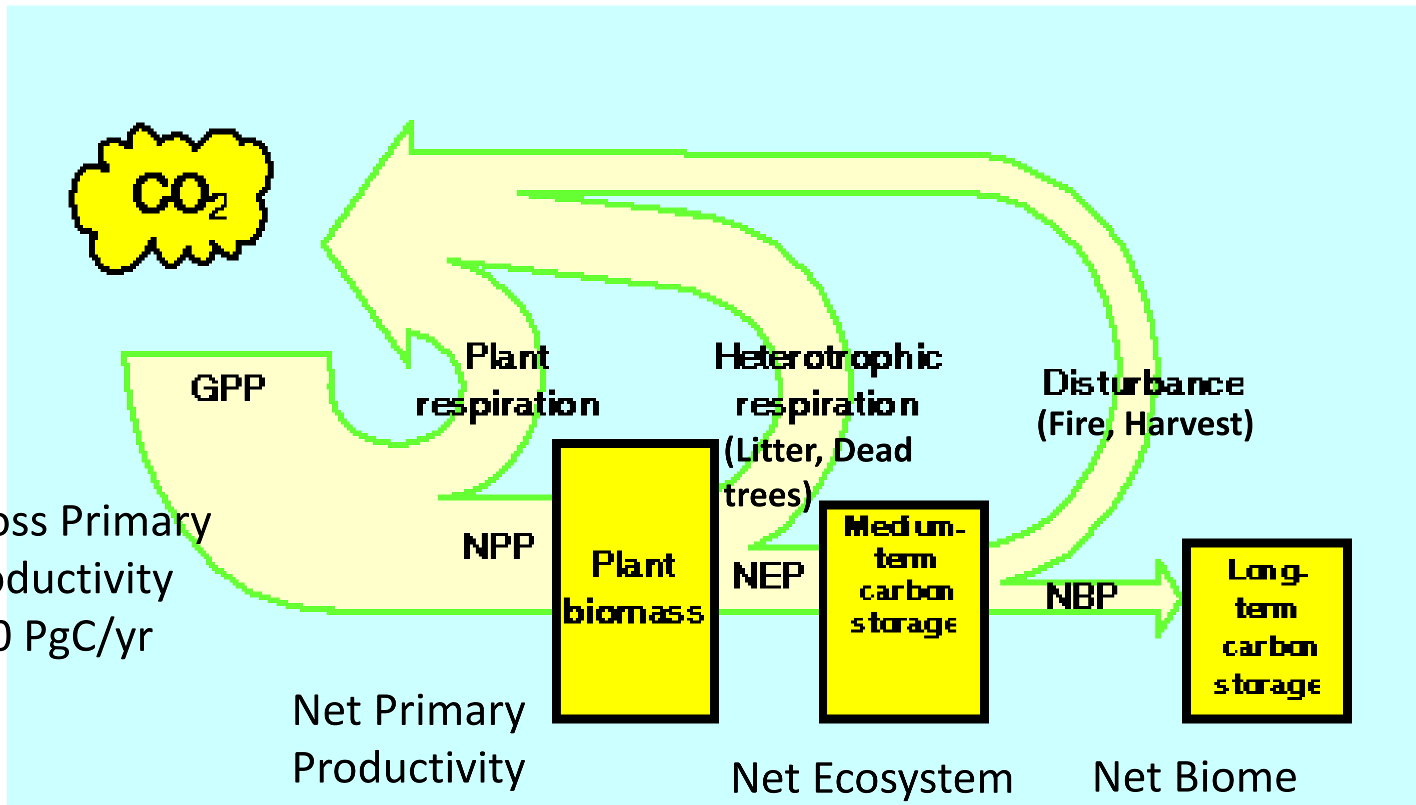
Global Forest Resources Assessment, FAO, 2010

Observations of terrestrial fluxes and biomass





CO_2 exchange with the terrestrial biosphere incorporates various processes and timescales



Gross Primary Productivity
120 PgC/yr

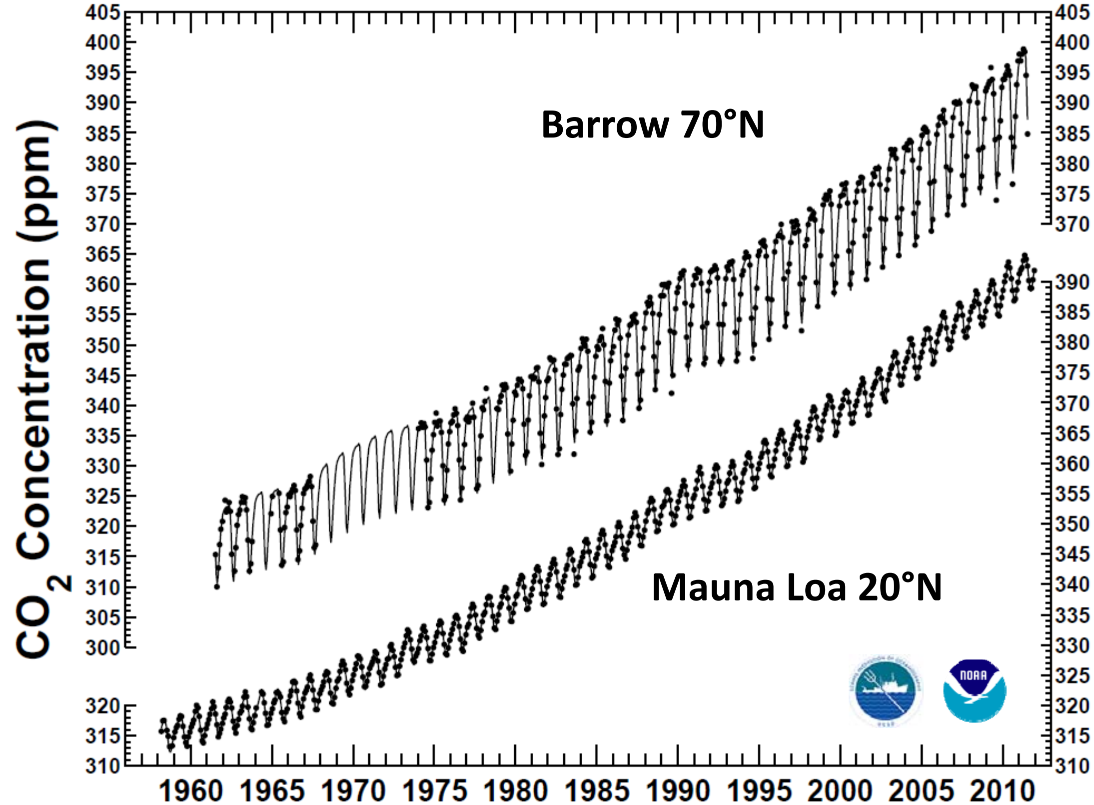
Net Primary Productivity
60 PgC/yr

Net Ecosystem Productivity
10 PgC/yr

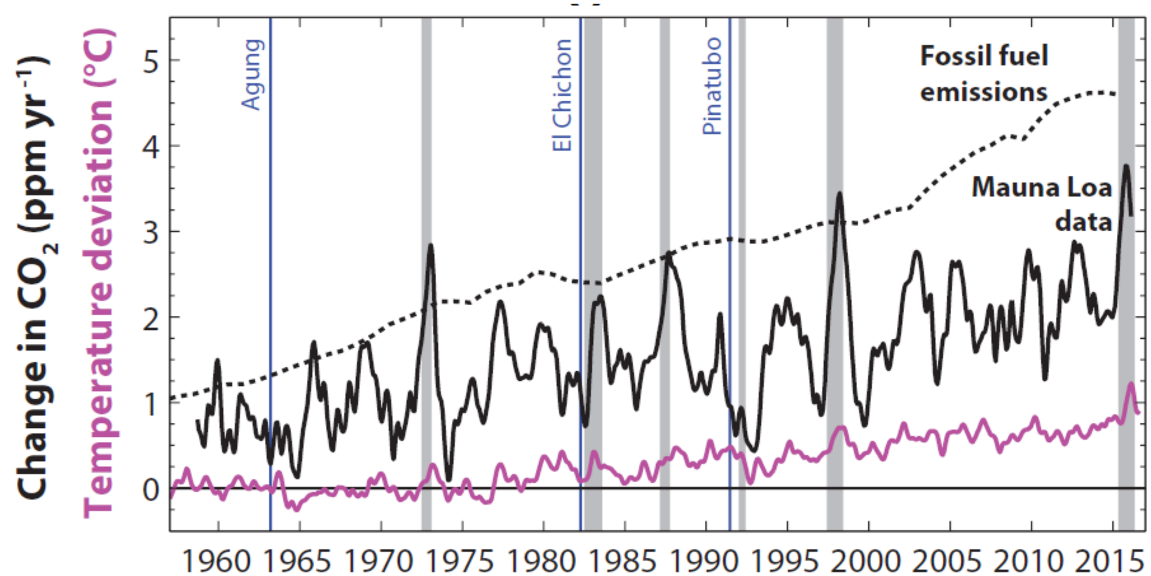
Net Biome Productivity
1.3 PgC/yr

Walker and Steffen 1997; IPCC 2013

Seasonal and interannual variations in biosphere exchange are visible in atmospheric CO_2



El Niño causes strong release from the biosphere during warm and dry conditions in the tropics



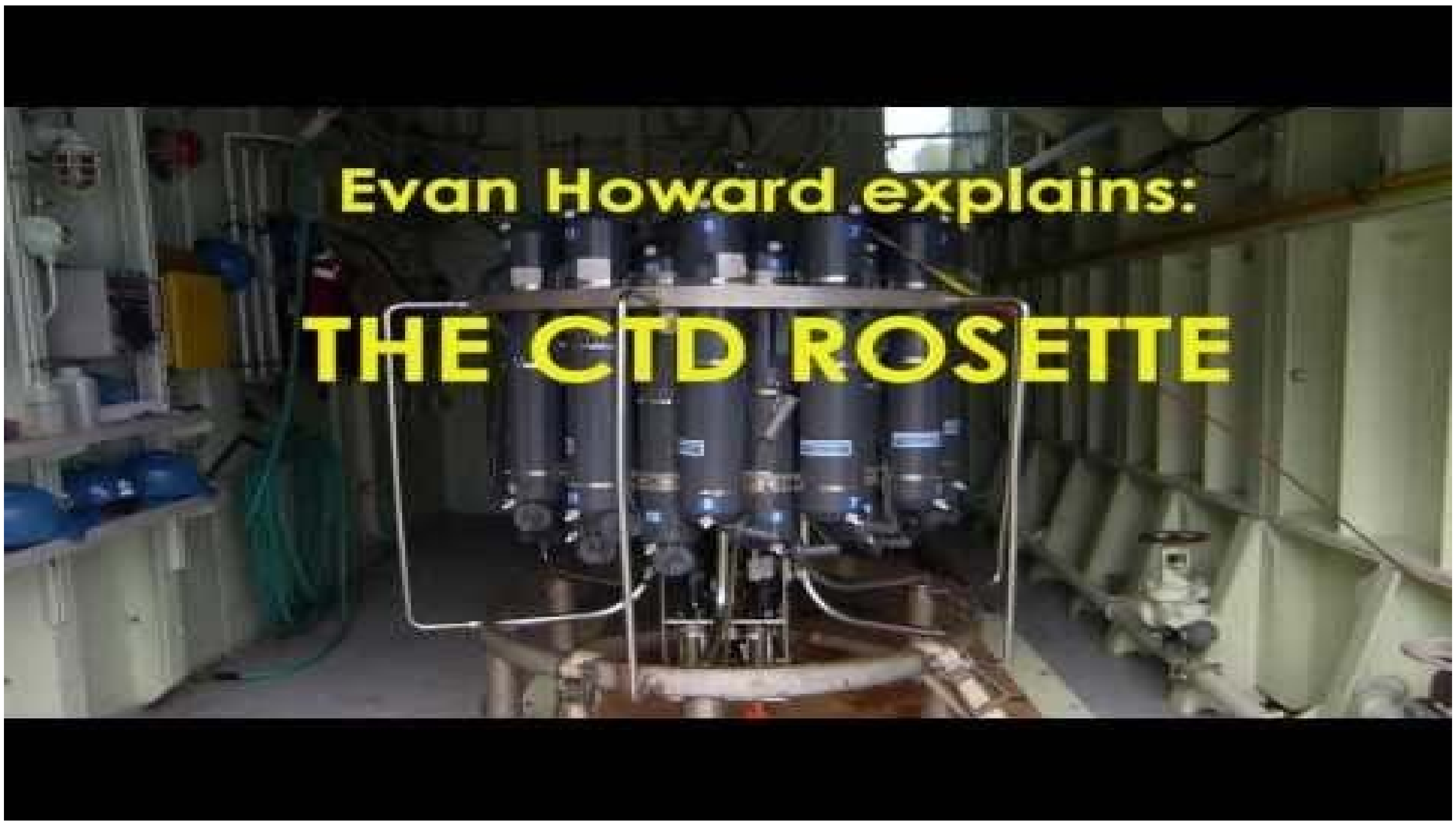
Scripps CO_2 Program; NASA; CDIAC; Graven 2016

Oceanic CO_2 and pH measurements use titrations and more advanced technologies

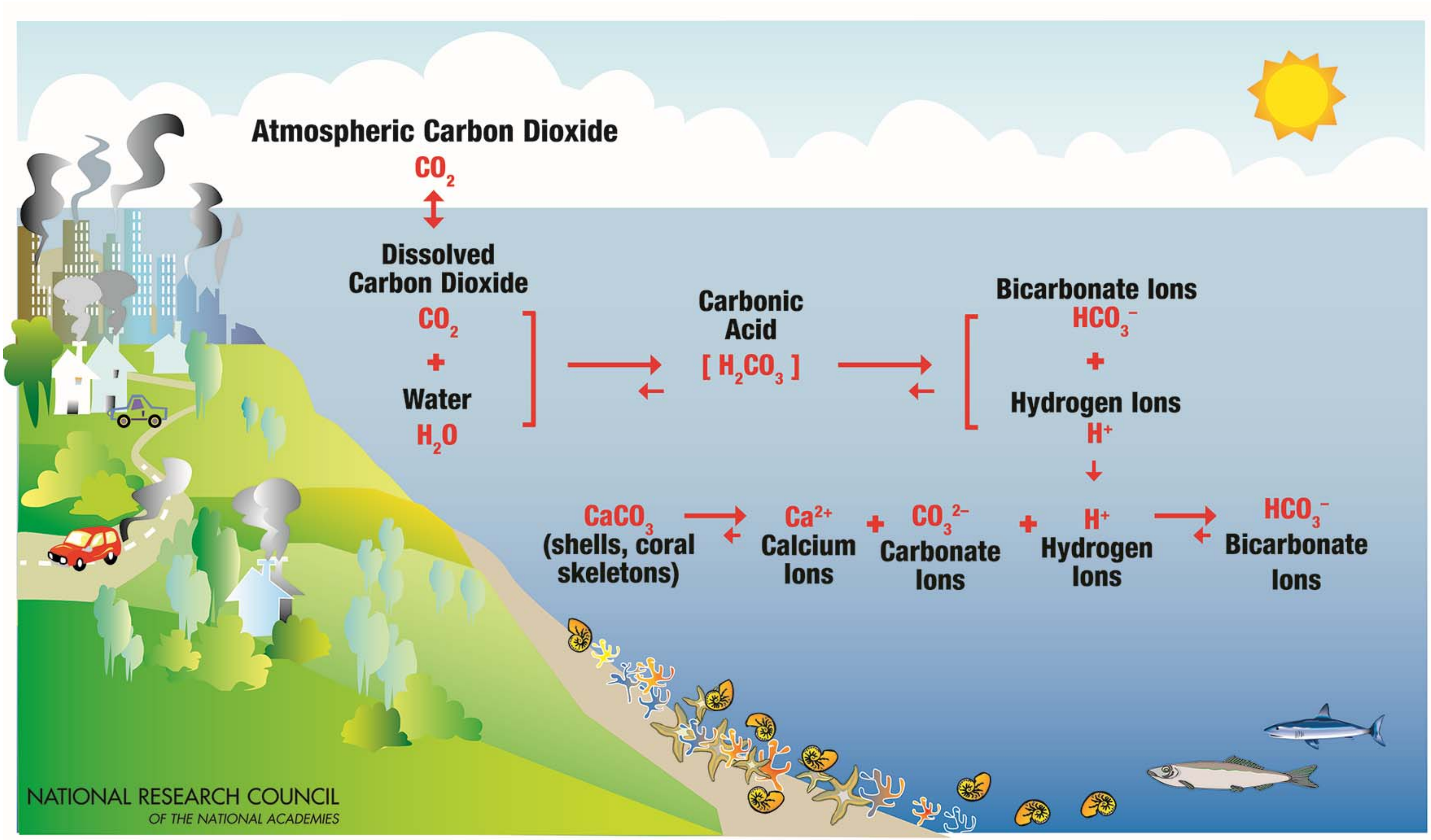
Images courtesy NOAA, NASA

Measuring conductivity, temperature, and depth (CTD) and sampling ocean water with a Rosette

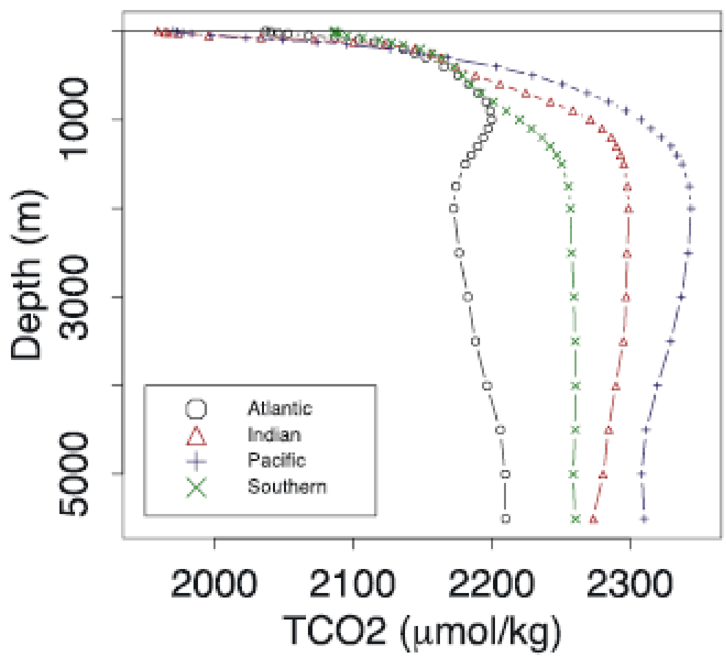
Video: https://www.youtube.com/watch?v=7N2UsPDczTw

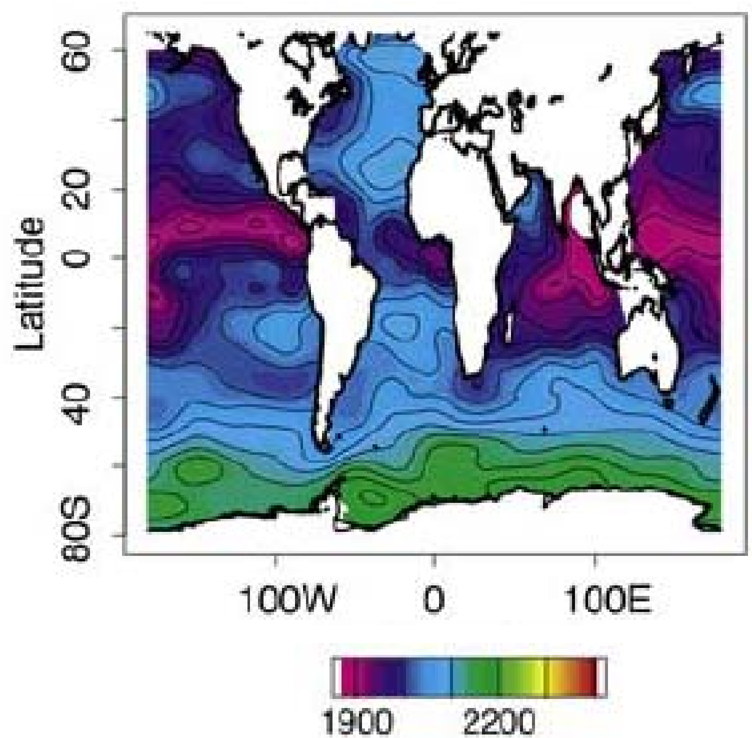


CO_2 in the ocean takes the form of several carbonate species



Dissolved Inorganic Carbon is concentrated in the deep ocean because of the solubility and biological pumps

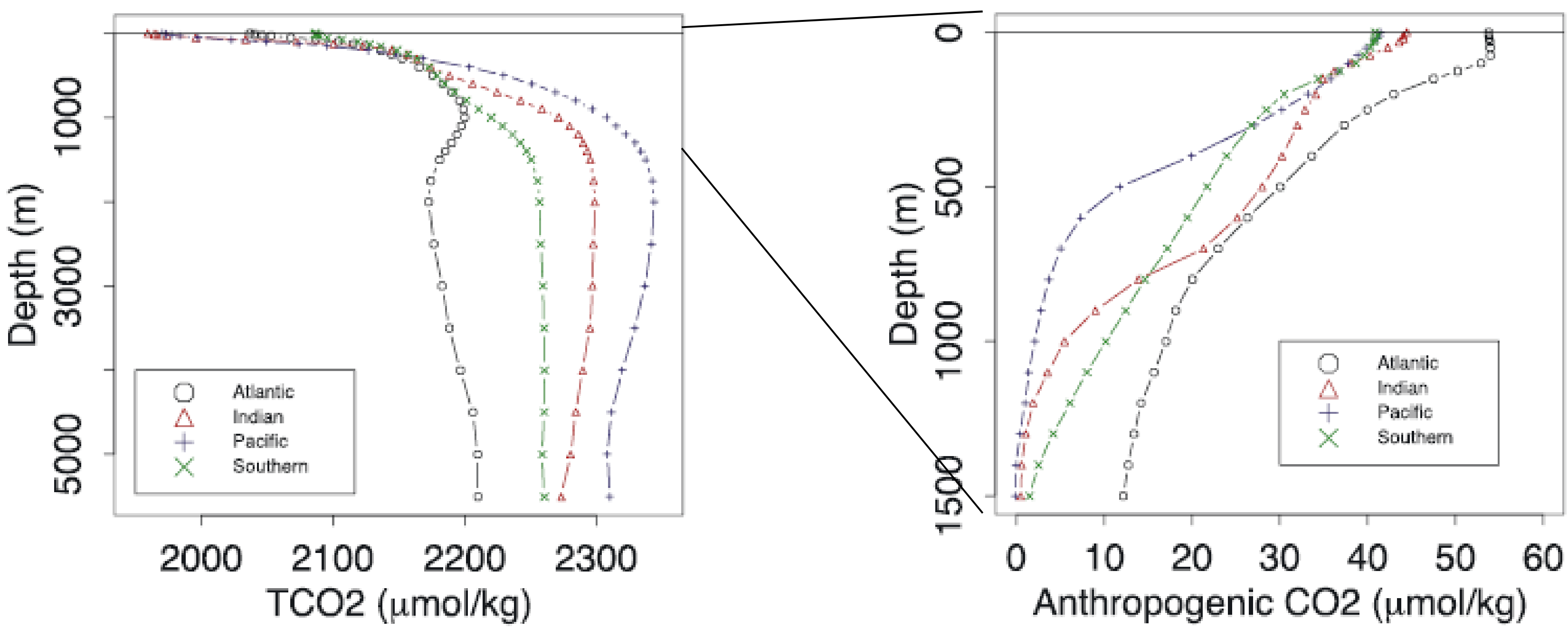




CO_2 solubility in the ocean is mainly a function of TCO_2 and Temperature

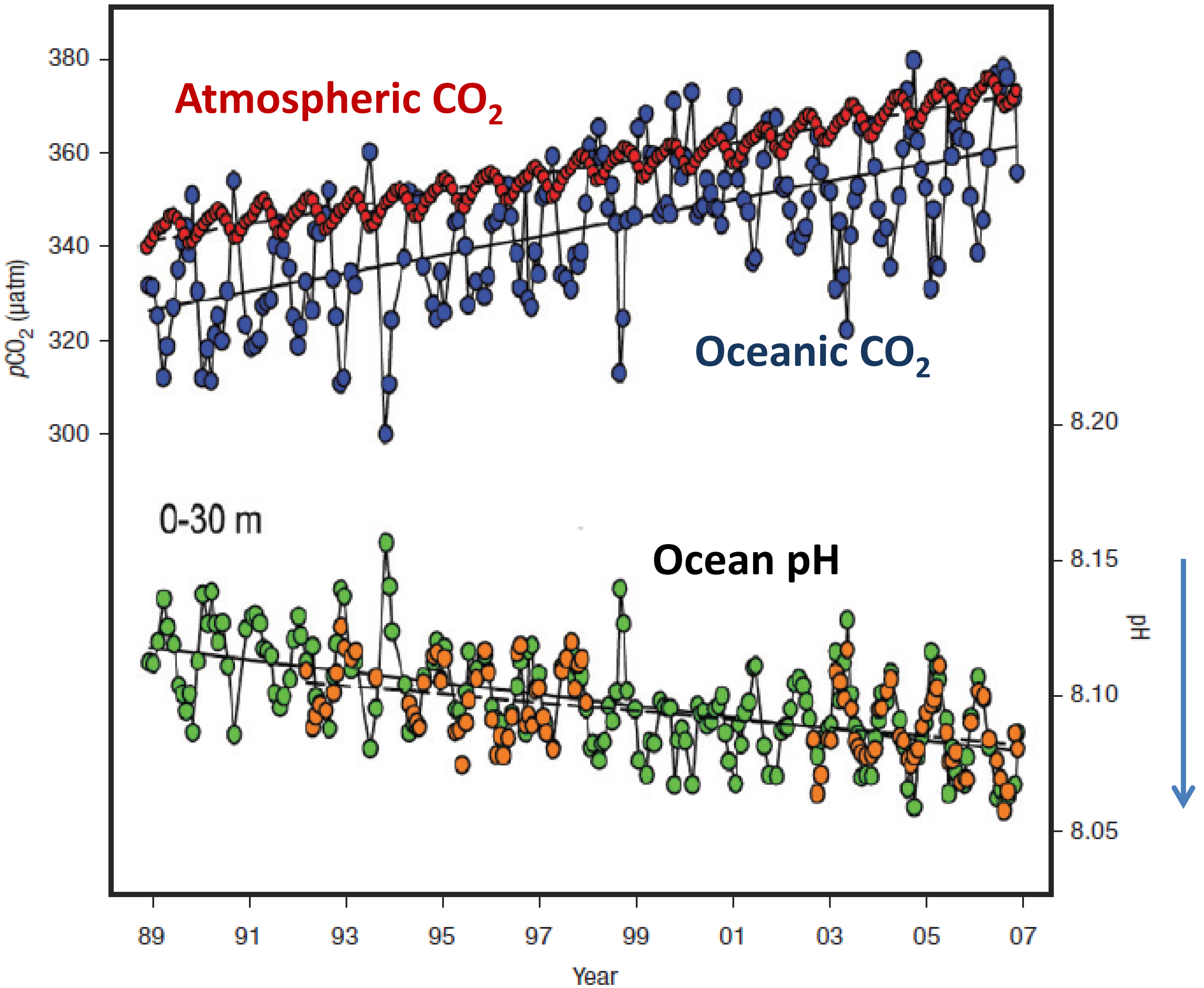
Key et al. 2004

Anthropogenic CO_2 uptake is driven by dissolution and ocean circulation



Key et al. 2004

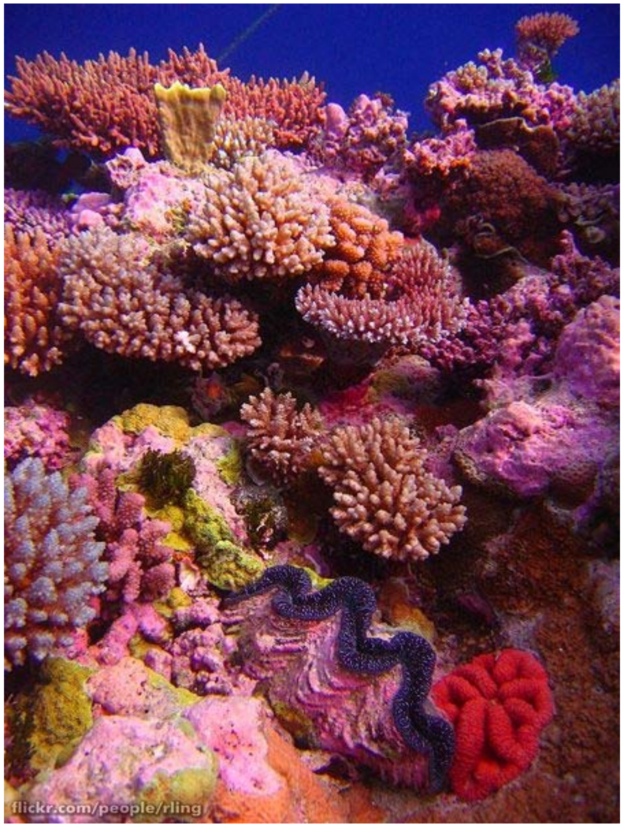
Observations show surface ocean CO_2 and H^+ are rising, and pH is decreasing: $pH = -\log[H^+]$



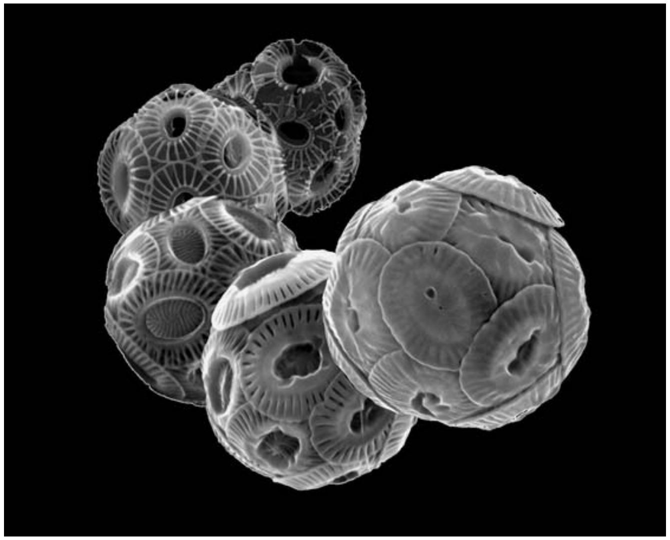
Observations from Station ALOHA, near Hawaii

+25% since the Industrial Revolution

Ocean acidification impacts on marine species



Hard corals largely composed of calcium carbonate; Soft corals contain calcium carbonate blended with protein



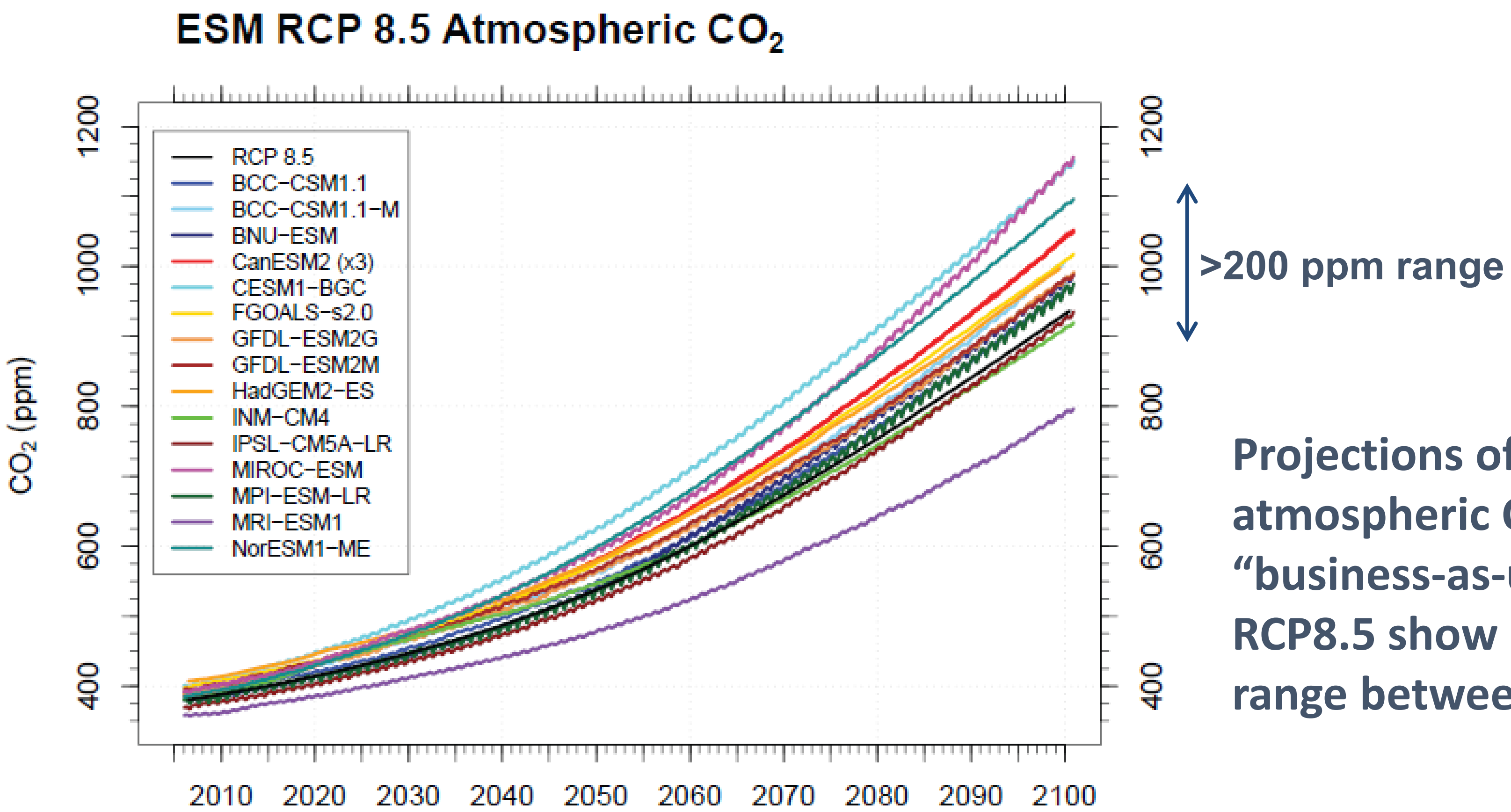
Calcifying phytoplankton

Basal resource in virtually all marine food webs

Vital source of energy for higher trophic levels

From E. O'Gorman

Carbon cycle processes are one of the main sources of uncertainty in projections of climate change

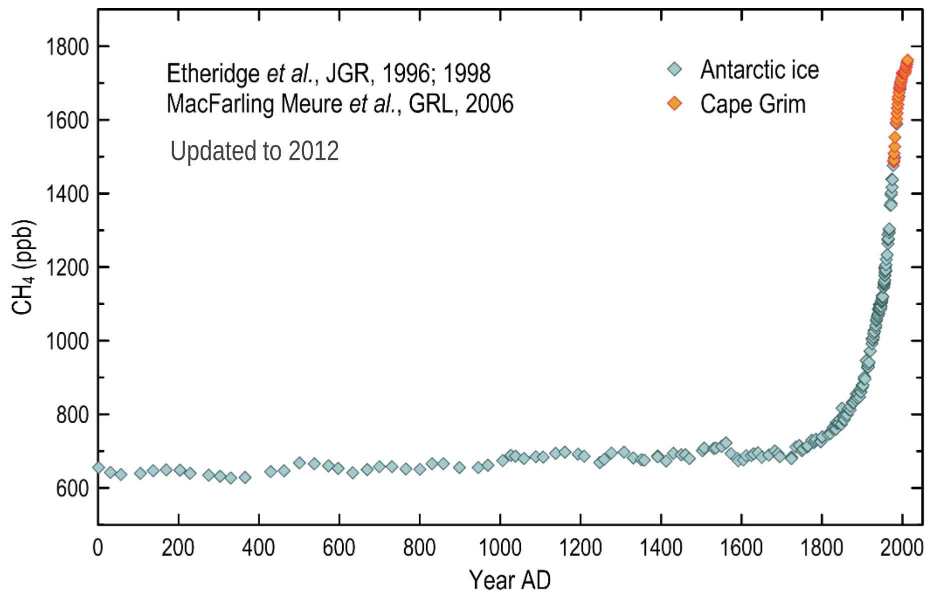


Projections of future atmospheric CO_2 under "business-as-usual" RCP8.5 show a wide range between models

Hoffman et al. (2014)

Atmospheric methane

- 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 emissions 2003-2012

Bottom-up budget
Process models, inventories, data driven methods
734 $TgCH_4$/yr [596-884]

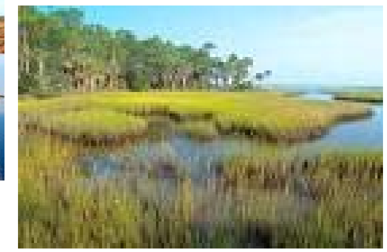
Mean [min-max range %]

($TgCH_4$/yr)

Top-down budget
Atmospheric inversions
559 $TgCH_4$/yr [540-568]

Natural wetlands	**185 [40%]**
Agriculture & waste	**195 [15%]**
Rice	30 [10%]
Enteric ferm & manure	106 [20%]
Landfills & waste	59 [20%]
Fossil fuel use	**121 [20%]**
Coal	42 [80%]
Gas & oil	79 [10%]
Biomass/biofuel burning	**30 [30%]**
Other natural emissions	**199 [90%]**
Fresh waters	122 [100%]
Wild animals	10 [100%]
Wild fires	3 [100%]
Termites	9 [120%]
Geological	40 [50%]
Oceans	3 [100%]
Permafrost	1 [100%]

Mean [uncertainty= min-max range %]

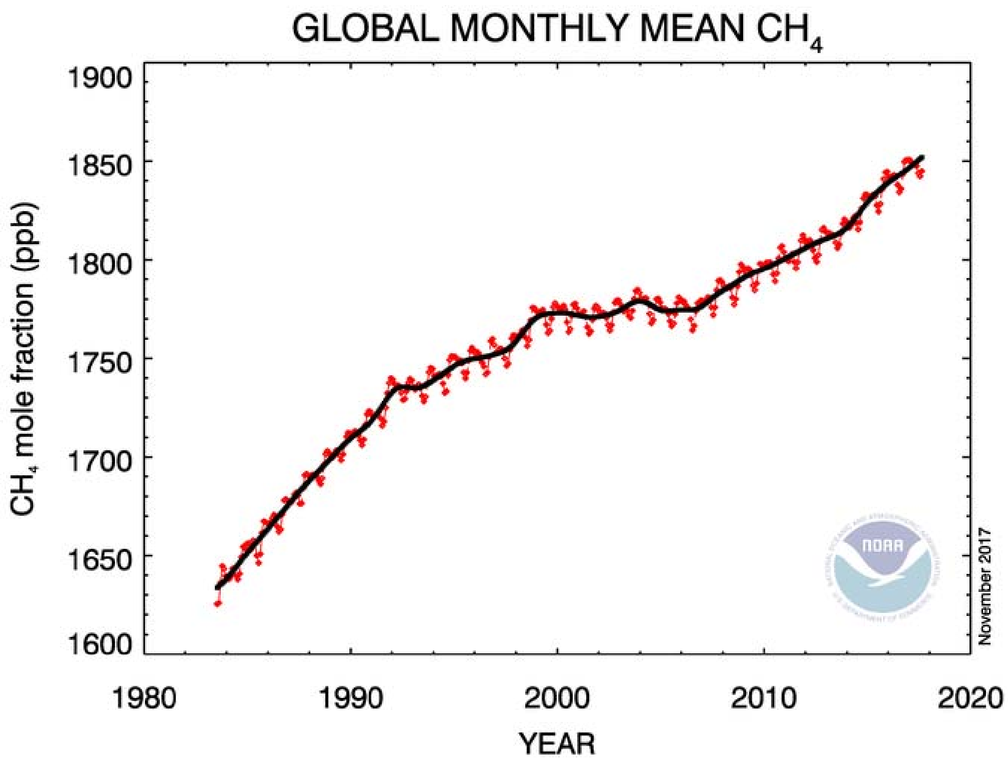








Source : *Saunois et al. 2016, ESSD*

CH_4 concentration stopped increasing for several years in the 2000s, then resumed



Hypotheses:

- Agricultural emissions (Schaefer et al. 2016)
- Fossil emissions from US fracking (Turner et al. 2016)
- Tropical wetland emissions (Nisbet et al. 2016)
- Variation in atmospheric OH and thus CH_4 removal by OH (Turner et al. 2017; Rigby et al. 2017), perhaps related to CO emissions (Gaubert et al. 2017)

Major research topics

- Where and how is anthropogenic CO_2 being taken up by the ocean and terrestrial biosphere?
- How will CO_2 and CH_4 exchanges be influenced by future emissions and climate change?
- How are marine organisms and food webs responding to ocean acidification, climate change, deoxygenation?
- How are terrestrial ecosystems responding to changing climate, nutrients, air pollution?
- What are the sources of CH_4 to the atmosphere and what caused the variation in CH_4 growth rate in the 2000s?

Other reading

Natalie Angier, Too much of a good thing, NYT, Sept. 22, 2014
http://www.nytimes.com/2014/09/23/science/carbon-dioxide-building-block-of-life-best-in-moderation.html?_r=1

Heather Graven, The carbon cycle in a changing climate, *Physics Today*.
http://physicstoday.scitation.org/doi/10.1063/PT.3.3365

The Global Carbon Project http://www.globalcarbonproject.org/

IPCC AR5 Chapter 6: Carbon and Other Biogeochemical Cycles
http://www.ipcc.ch/report/ar5/wg1/

David Archer, *The Global Carbon Cycle*, Princeton Primers in Climate, Princeton University Press,
Chapter 1: http://press.princeton.edu/chapters/s9379.pdf

Practice questions

1. Write down and explain the key reactions in the global carbon cycle.
2. What is the difference between gross and net fluxes of carbon? Give some examples of how net fluxes change if they are integrated over different timescales.
3. What is the definition of the airborne fraction and what is its value? In one future scenario, CO_2 emissions will increase to 20 PgC/yr by 2050. What would the atmospheric growth rate of CO_2 be in 2050 if the airborne fraction remained constant? What are some potential changes to ocean and terrestrial biosphere processes that could cause the airborne fraction to increase?