Global Carbon Cycle

AOSC 680

Ross Salawitch

Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/fall2022
https://umd.instructure.com/courses/1327017

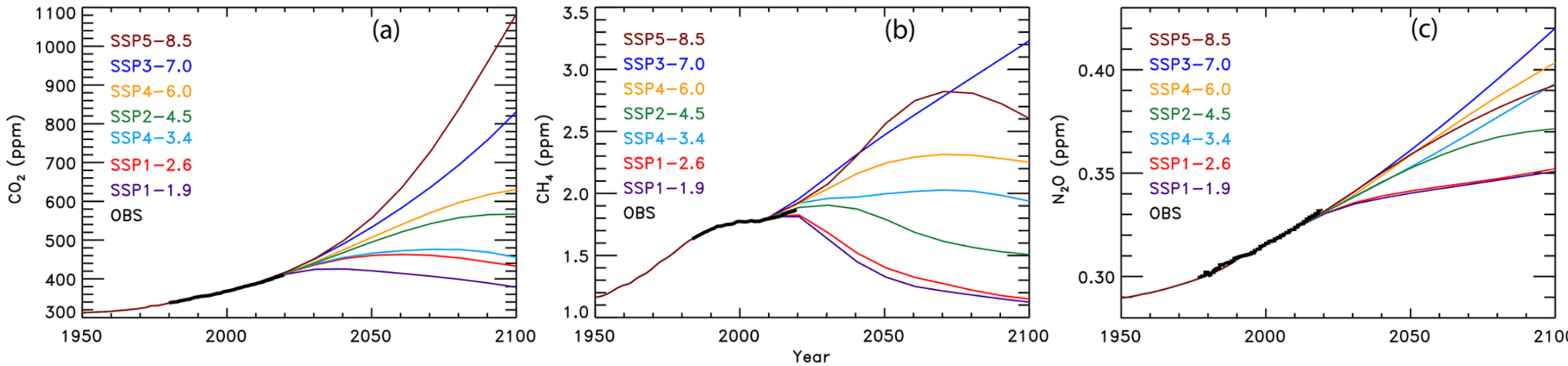
Goals for today:

- **Overview of the Global Carbon Cycle "scratching below the surface"**
- **Ocean and land uptake of CO_2 : past and future**
- **Policy to reduce emissions of CO_2**

Lecture 5

15 September 2022

Background



- SSP: Share Socioeconomic Pathways (SSPs)
  Number represents ΔRF of climate (W m^{-2}) at the end of this century
- GHG mixing ratio time series for CO_2, CH_4, N_2O, as well as CFCs, HCFCs, and HFCs that are provided to climate model groups

Figure from McBride et al., 2021: https://esd.copernicus.org/articles/12/545/2021

Motivation 1

CO_2 is long lived: society must reduce emissions soon or we will be committed to dramatic, future increases in $[CO_2]$

Curves for which $[CO_2]$ levels off at ~550 ppm or less have emissions peaking NOW !

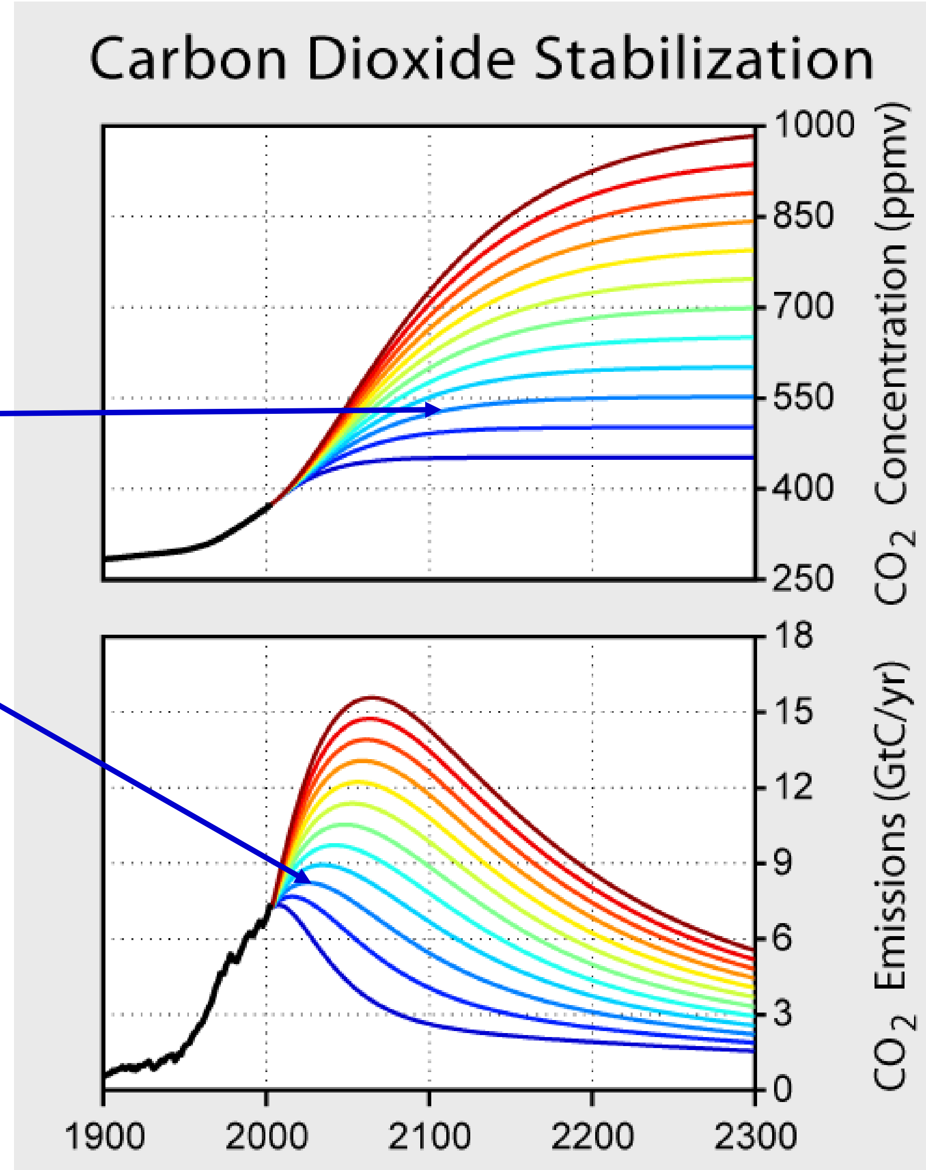
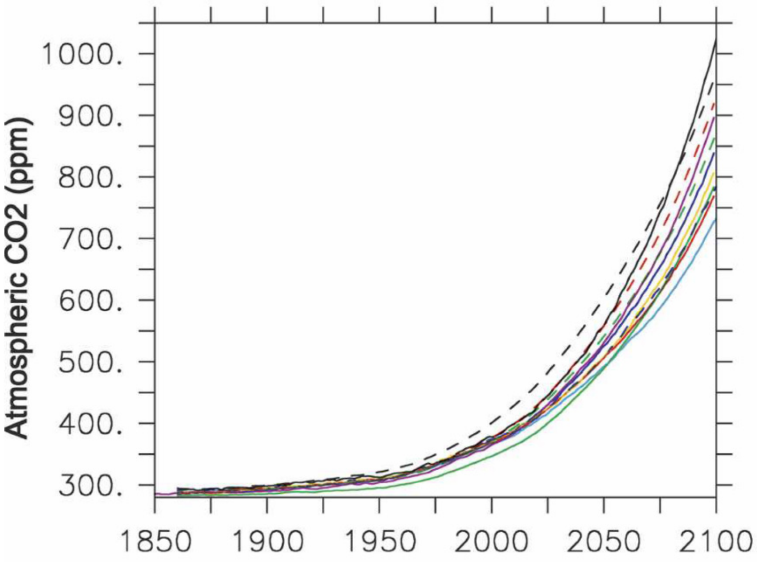
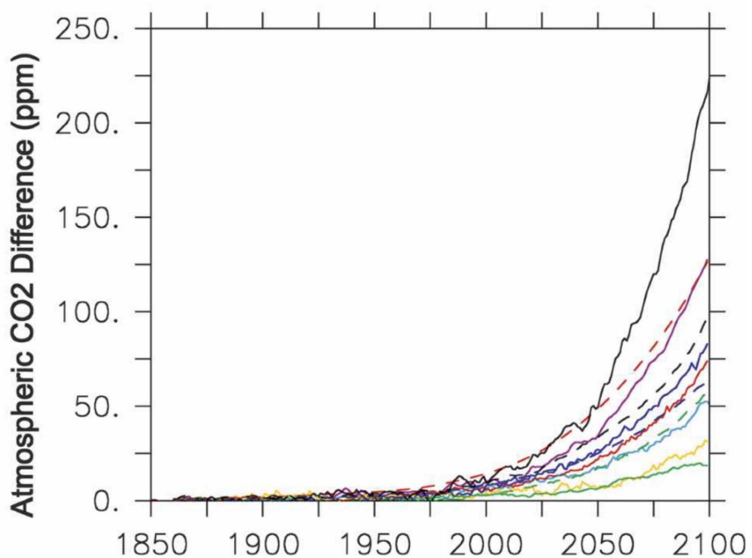


Image: “Global Warming Art” : http://archive.is/JT5rO

Motivation 2



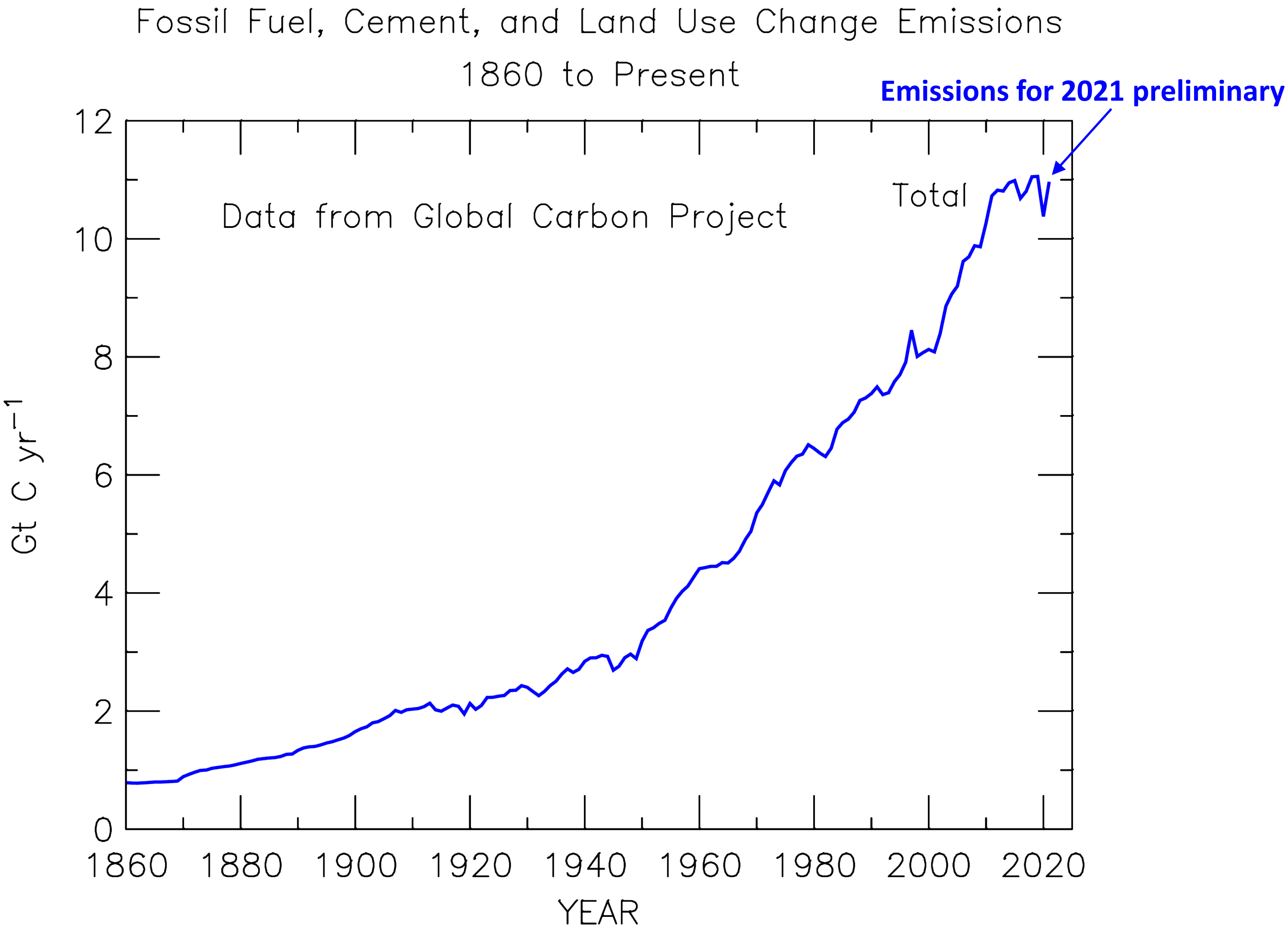


- Prior slides examined atmospheric CO_2 from a single model of the global carbon cycle

- Friedlingstein et al. (2006) compared CO_2 from **11** different coupled climate-carbon cycle models, each constrained by the *same* specified time series of anthropogenic CO_2 emission and found:

  1) future climate change will reduce the efficiency of the *Earth system* to absorb the anthropogenic carbon perturbation

  2) difference in CO_2 between a simulation using an interactive carbon-cycle and another run with a non-interactive carbon-cycle varies from 20 to 200 ppm among these **11** models (yikes!)



Note: Gt is an abbreviation for giga tons, or 10^9 tons. Here we are using *metric tons*:
1 metric ton = 10^3 kg ; therefore, 1 Giga ton = 10^{15} g, where g is grams.

Modern CO_2 Record

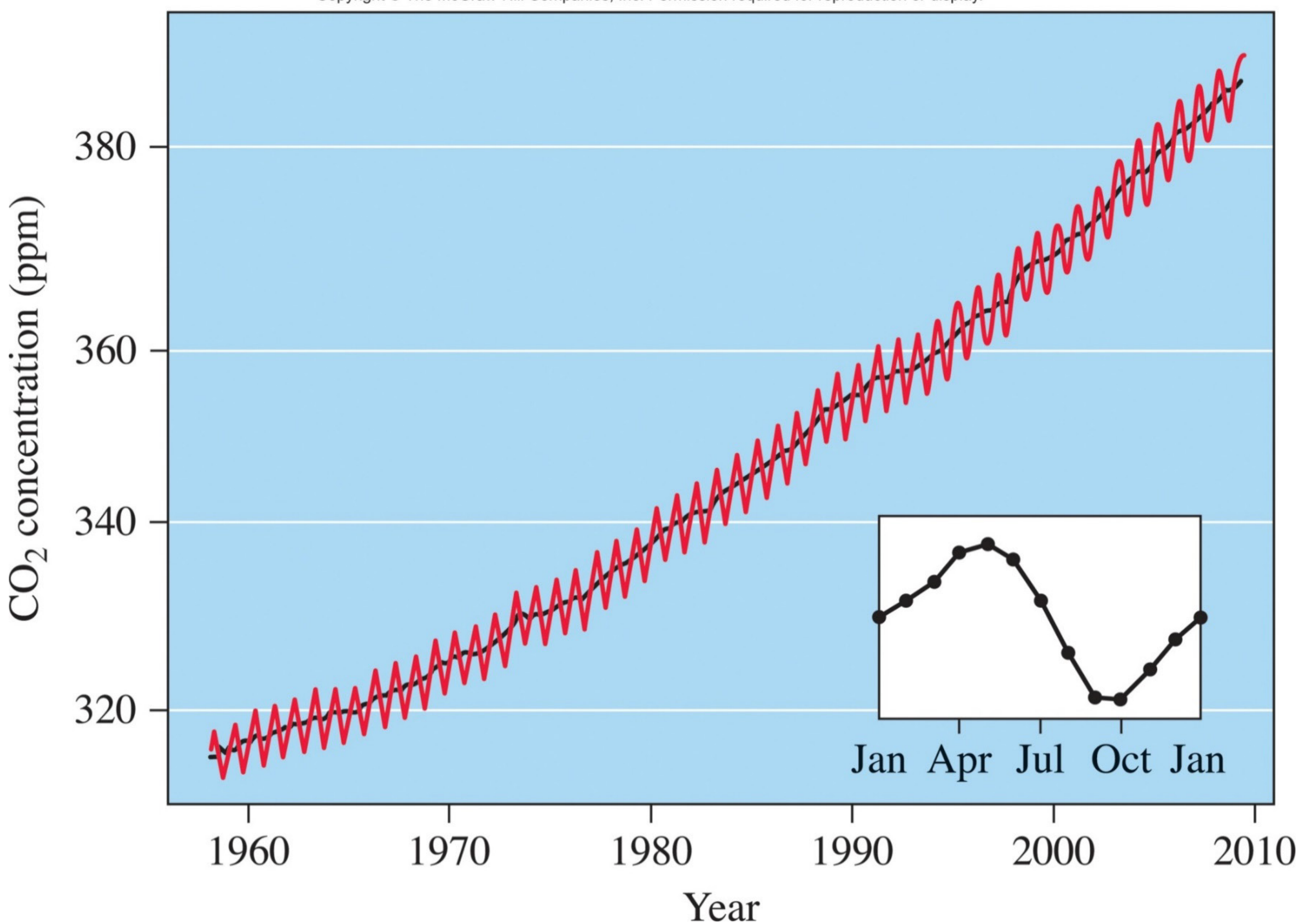
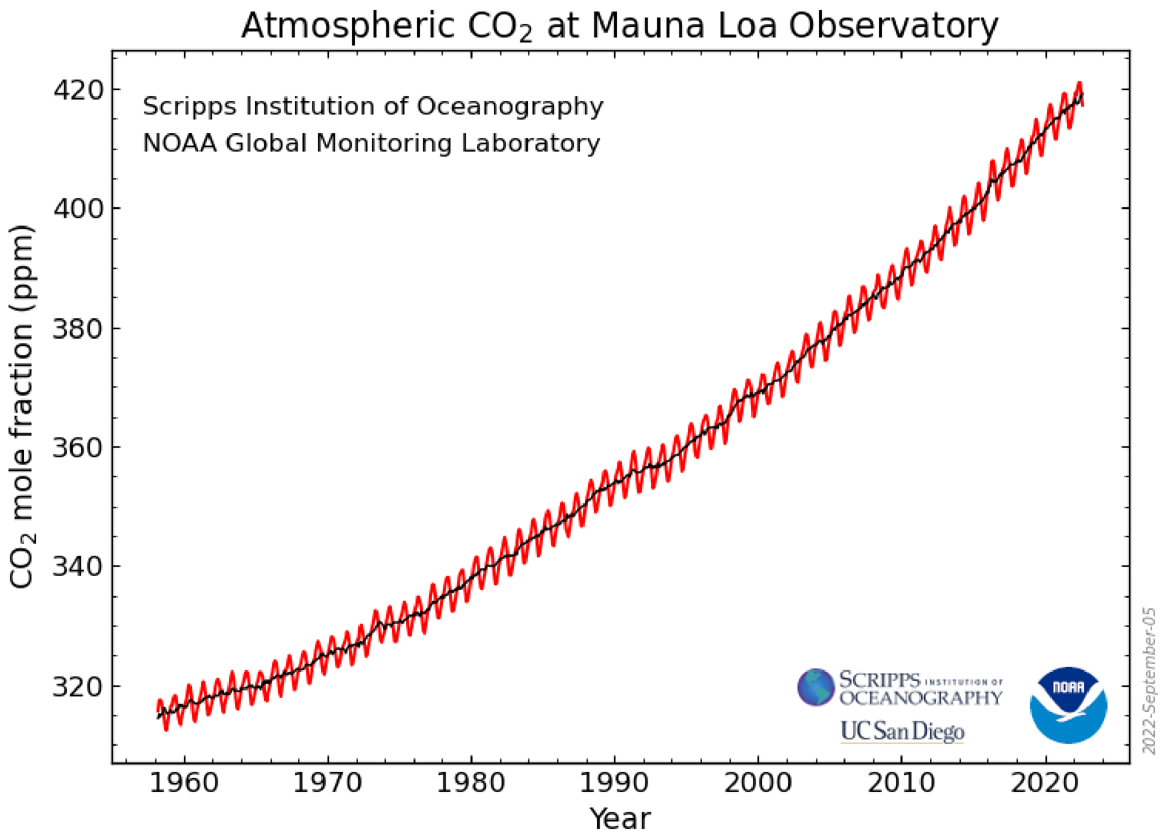


Figure 3.3, Chemistry in Context

Modern CO_2 Record

CO_2 at MLO on 4 Sep 2022: 416.68 parts per million (ppm)
CO_2 at MLO on 4 Sep 2021: 413.43 parts per million (ppm)

ΔCO_2 = 3.25 ppm per year
or 0.8 % per year



Legacy of Charles Keeling, Scripps Institution of Oceanography, La Jolla, CA
https://www.esrl.noaa.gov/gmd/webdata/ccgg/trends/co2_data_mlo.png
See also https://www.co2.earth/daily-co2

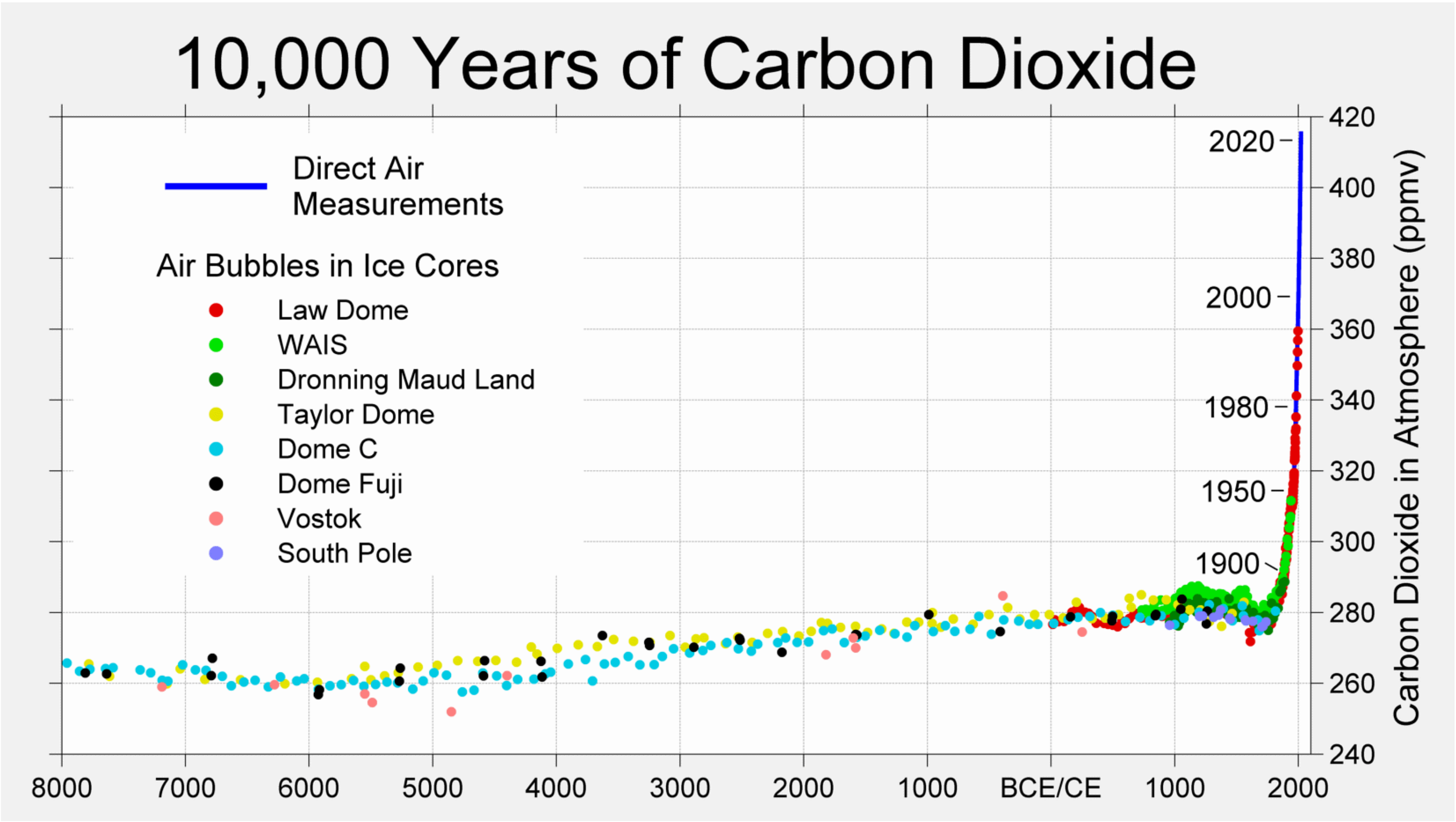
Carbon Dioxide (CO_2): The Past Eight Millennium

Combustion:

Gasoline (octane) $2\ C_8H_{18} + 25\ O_2$ + Small Source of Energy → $16\ CO_2 + 18\ H_2O$ + Lots of Energy

Natural gas (methane) $CH_4 + 2\ O_2$ + Small Source of Energy → $CO_2 + 2\ H_2O$ + Lots of Energy

Coal $C_{135}H_{96}O_9NS + 309\ O_2$ + Small Source of Energy → $135\ CO_2 + 48\ H_2O$ + Lots of Energy + Other Pollutants



https://twitter.com/RARohde/status/1443890623371677698

Robert Rohde: https://twitter.com/RARohde

Modern CO_2 Record

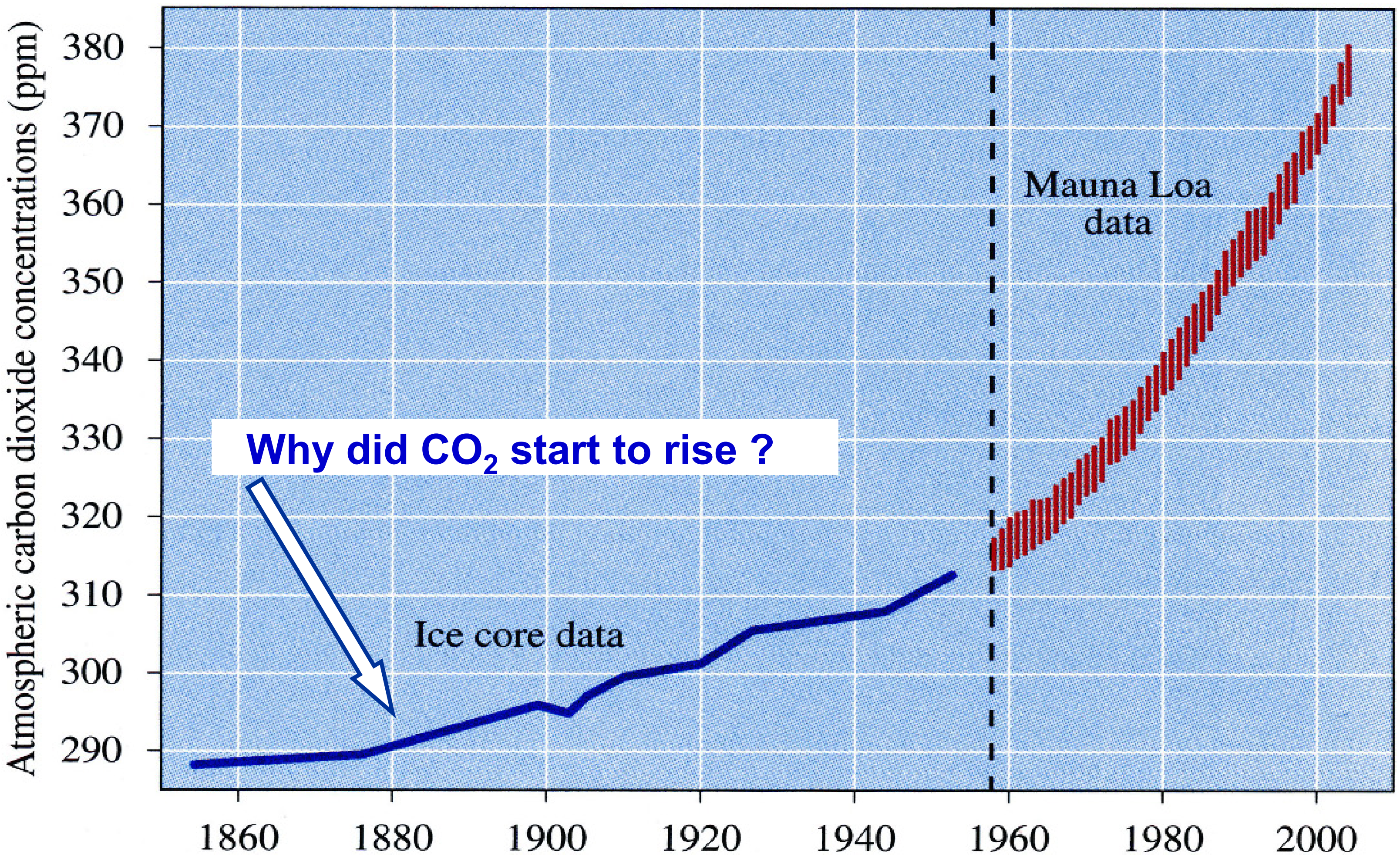
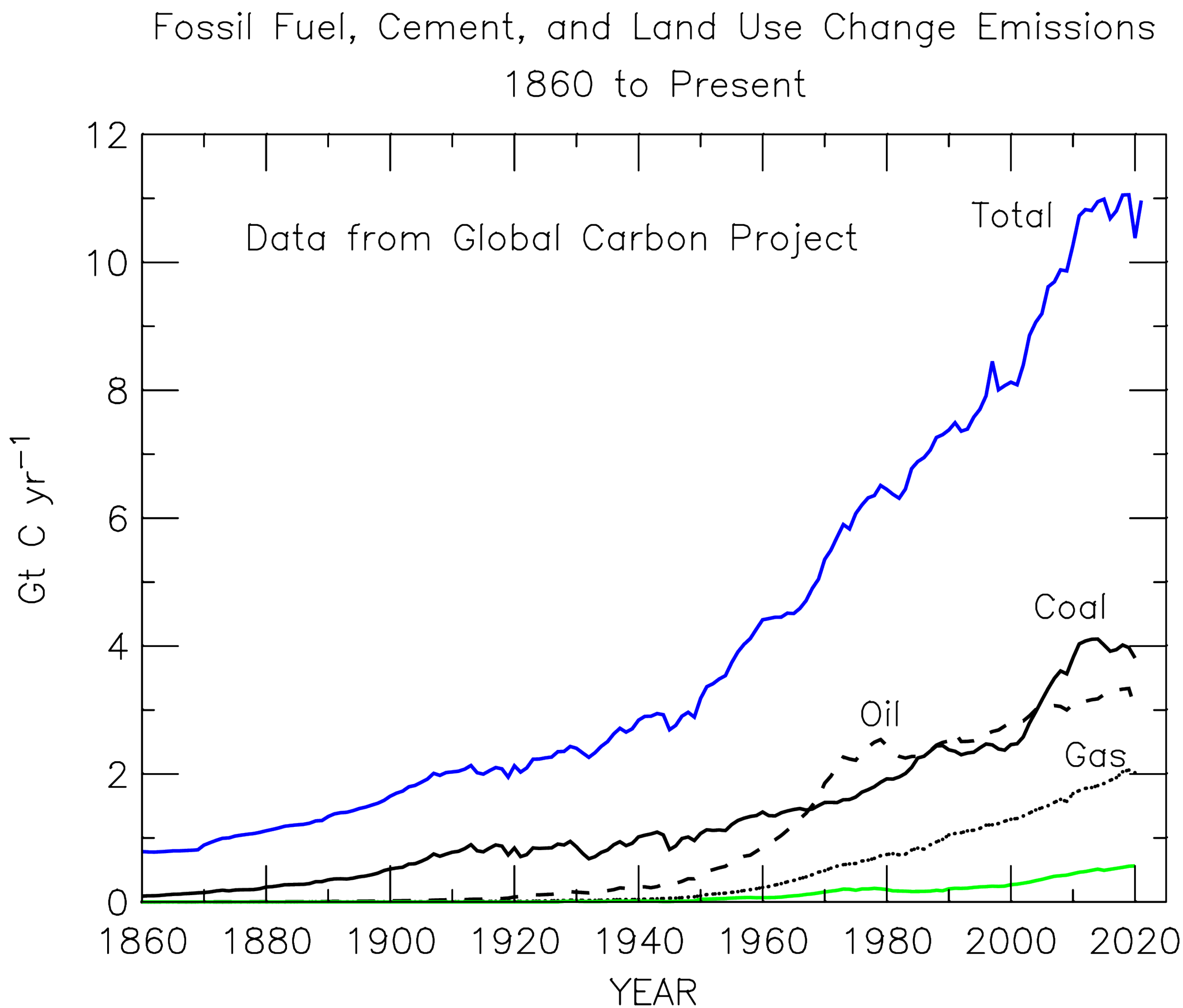


Figure 3.5, *Chemistry in Context, 7th Edition*


Fossil Fuel, Cement, and Land Use Change Emissions
1860 to Present
Data from Global Carbon Project
Total
Coal
Oil
Gas
Gt C yr^{-1}
YEAR
0
2
4
6
8
10
12
1860
1880
1900
1920
1940
1960
1980
2000
2020

Human "Fingerprints" on Atmospheric CO_2

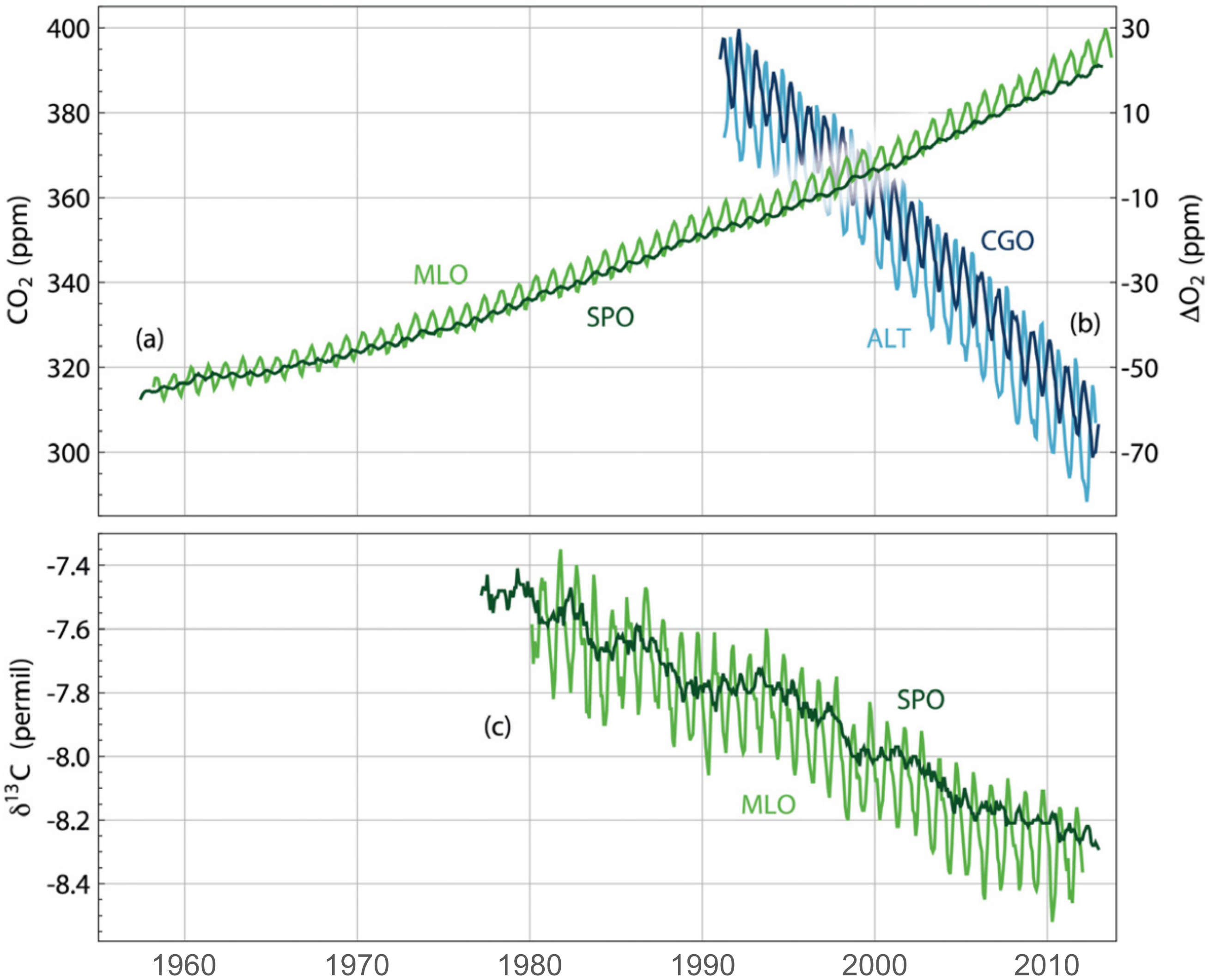
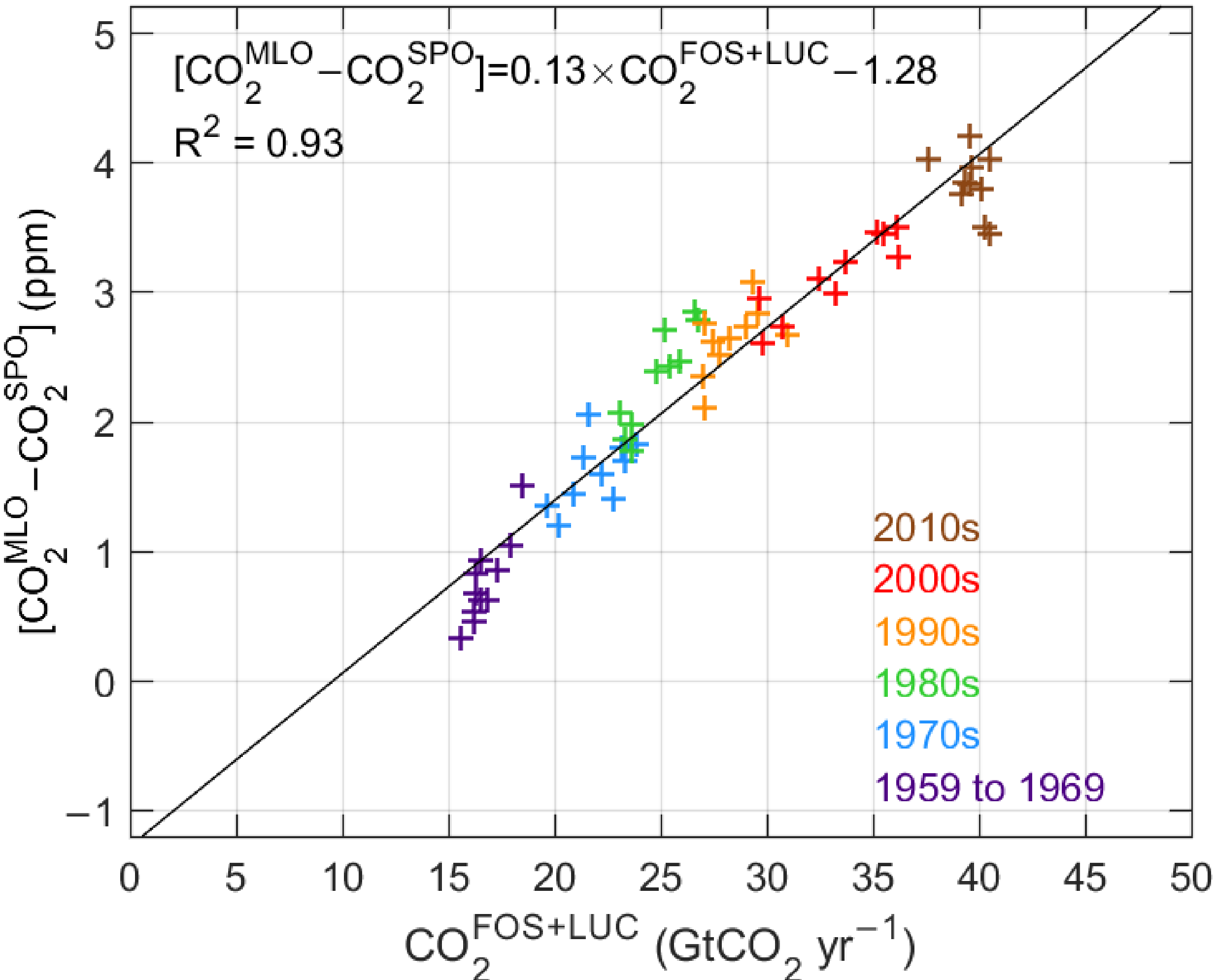


Figure 3.4 Atmospheric concentrations observed at representative stations of (a) carbon dioxide from Mauna Loa (MLO) Northern Hemisphere and South Pole (SPO) Southern Hemisphere; (b) Oxygen from Alert (ALT) Canada, 82°N, and Cape Grim (CGO), Australia, 41°S; (c) $^{13}C/^{12}C$ from Mauna Loa (MLO) and South Pole (SPO) stations.

Fig 3.4, Houghton

Human “Fingerprints” on Atmospheric CO_2



MLO: Mauna Loa Observatory
SPO: South Pole Observatory
FOS: Fossil Fuel Combustion
LUC: Land Use Change (Deforestation)

Fig 1.8 updated, *Paris Beacon of Hope*

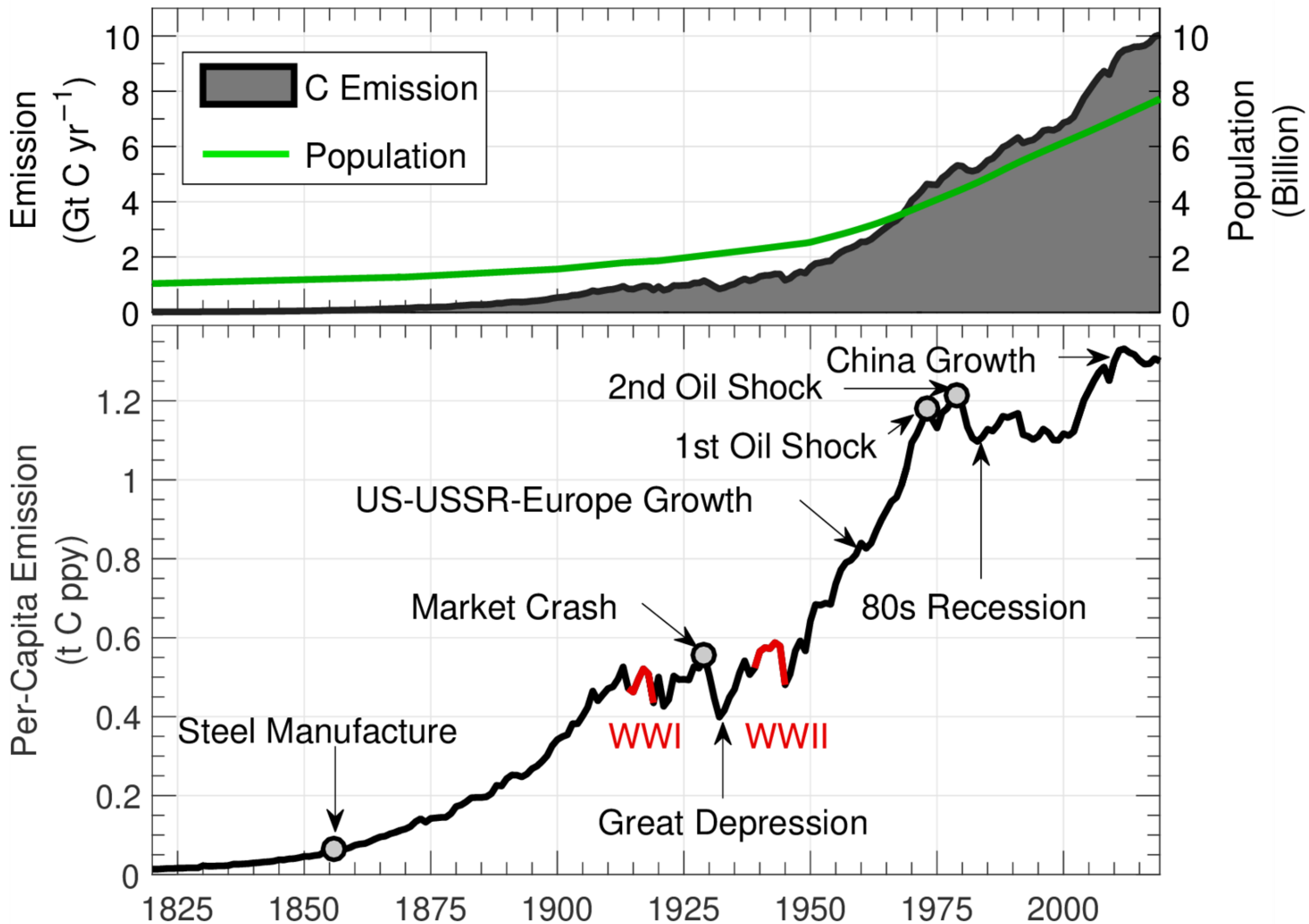
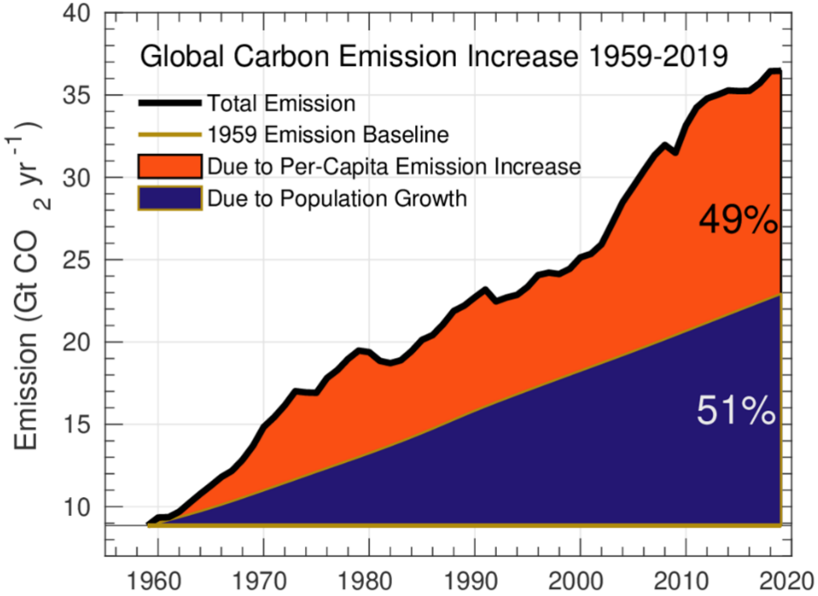


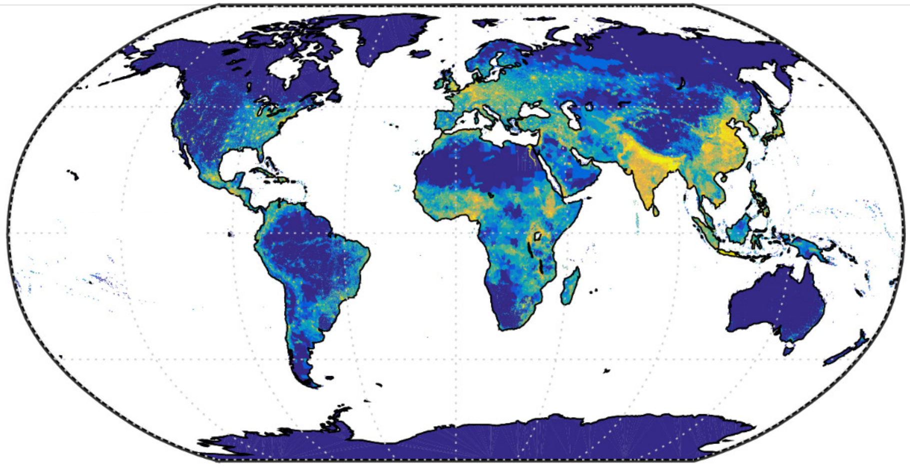
Figure courtesy Walt Tribett

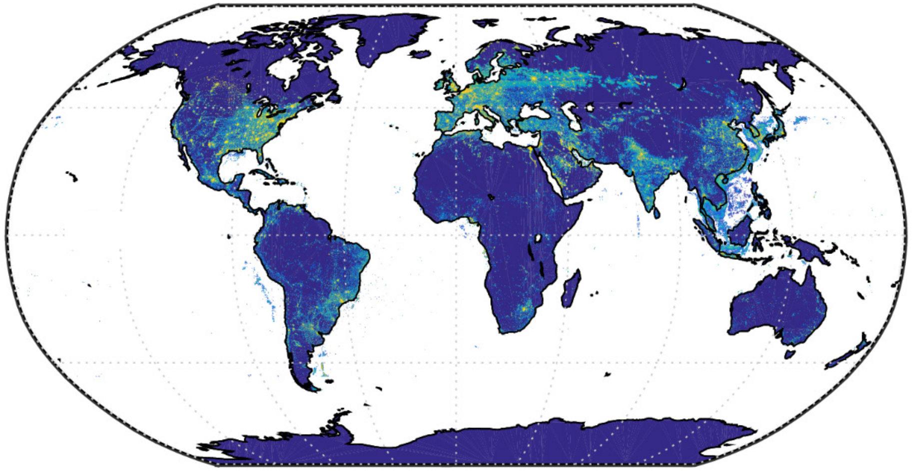
After Fig 3.1 *Paris Beacon of Hope*

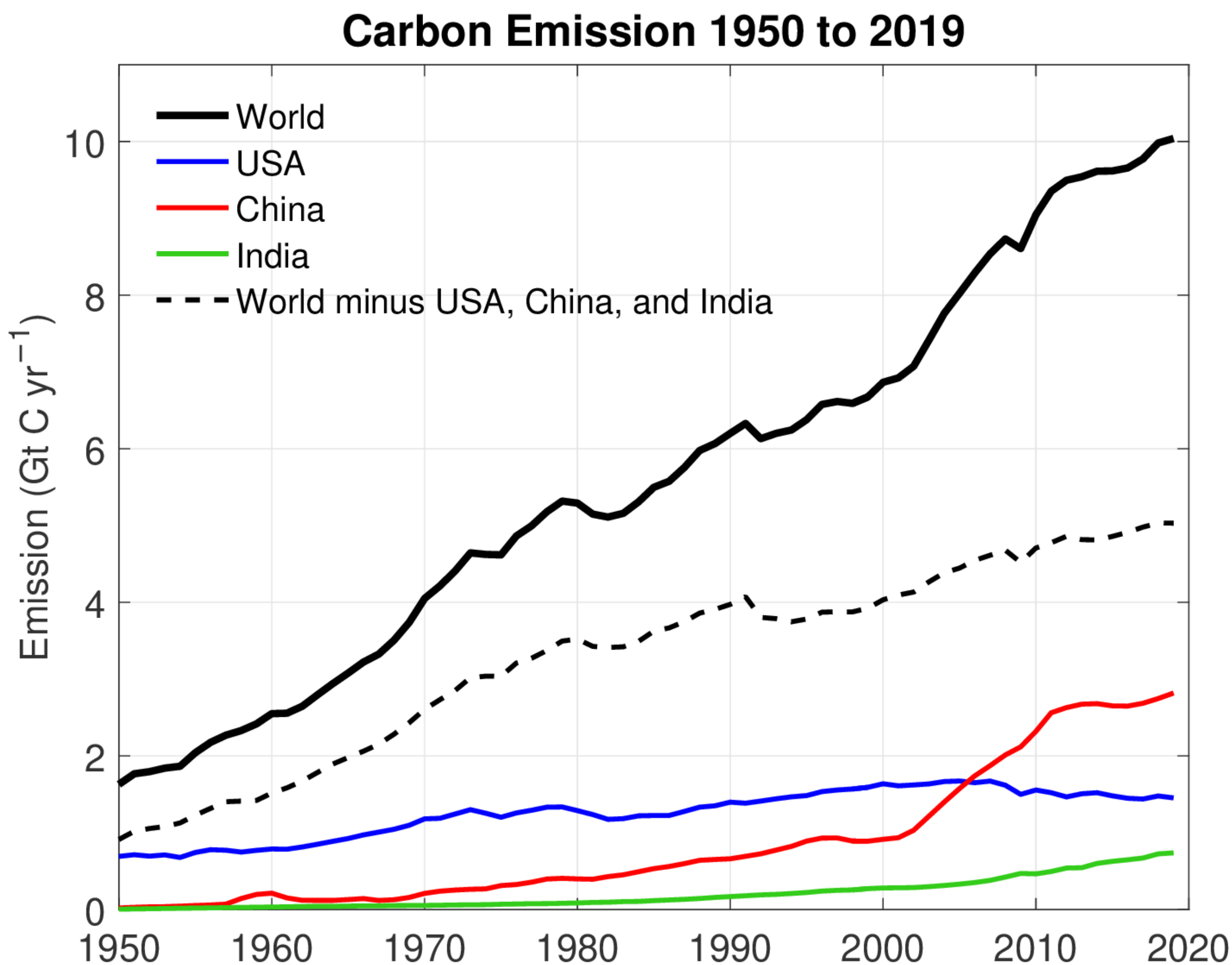
Fossil Fuel Emissions



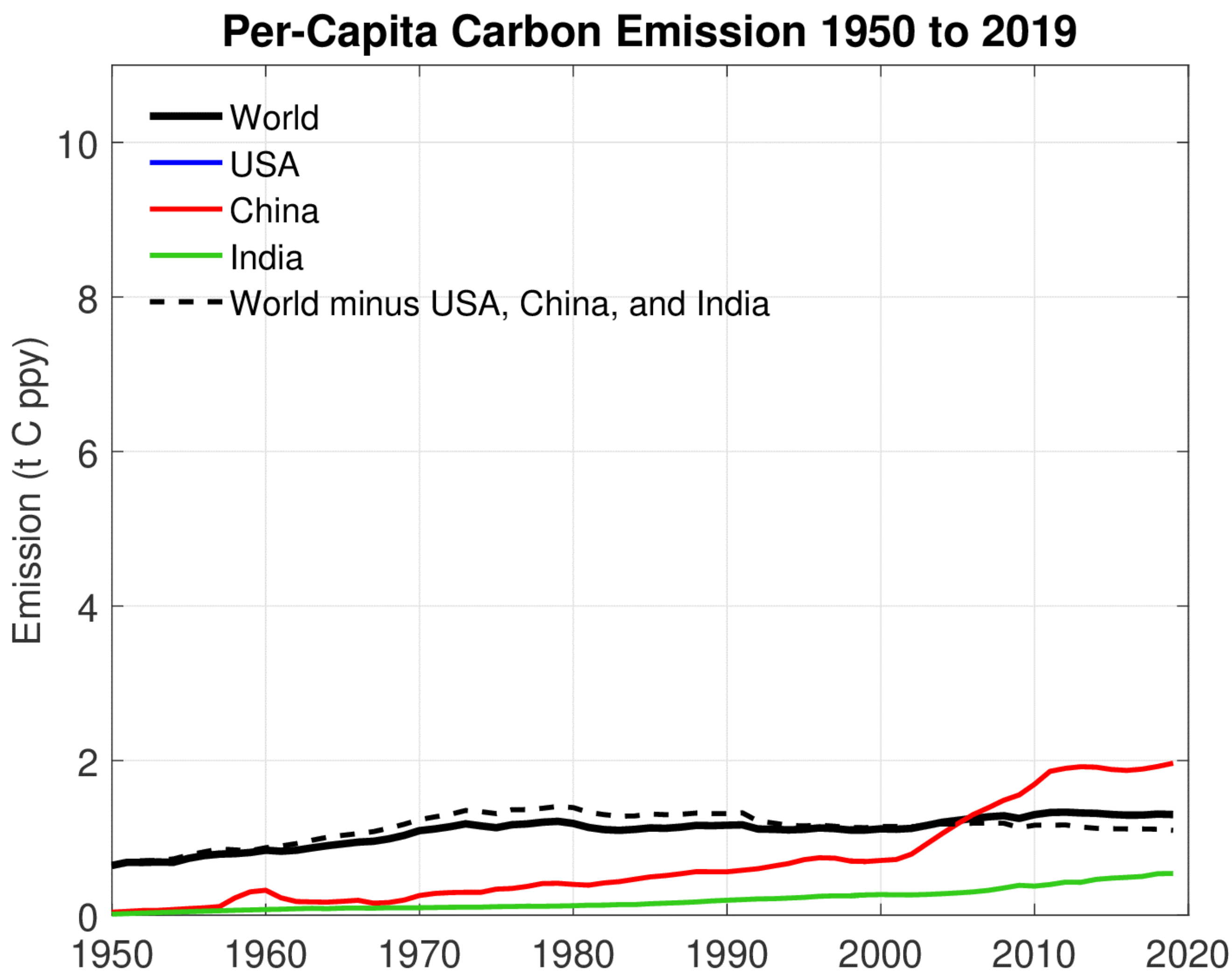
Population increase & **per-capita rise** both contribute, nearly equally to the global rise in C emissions



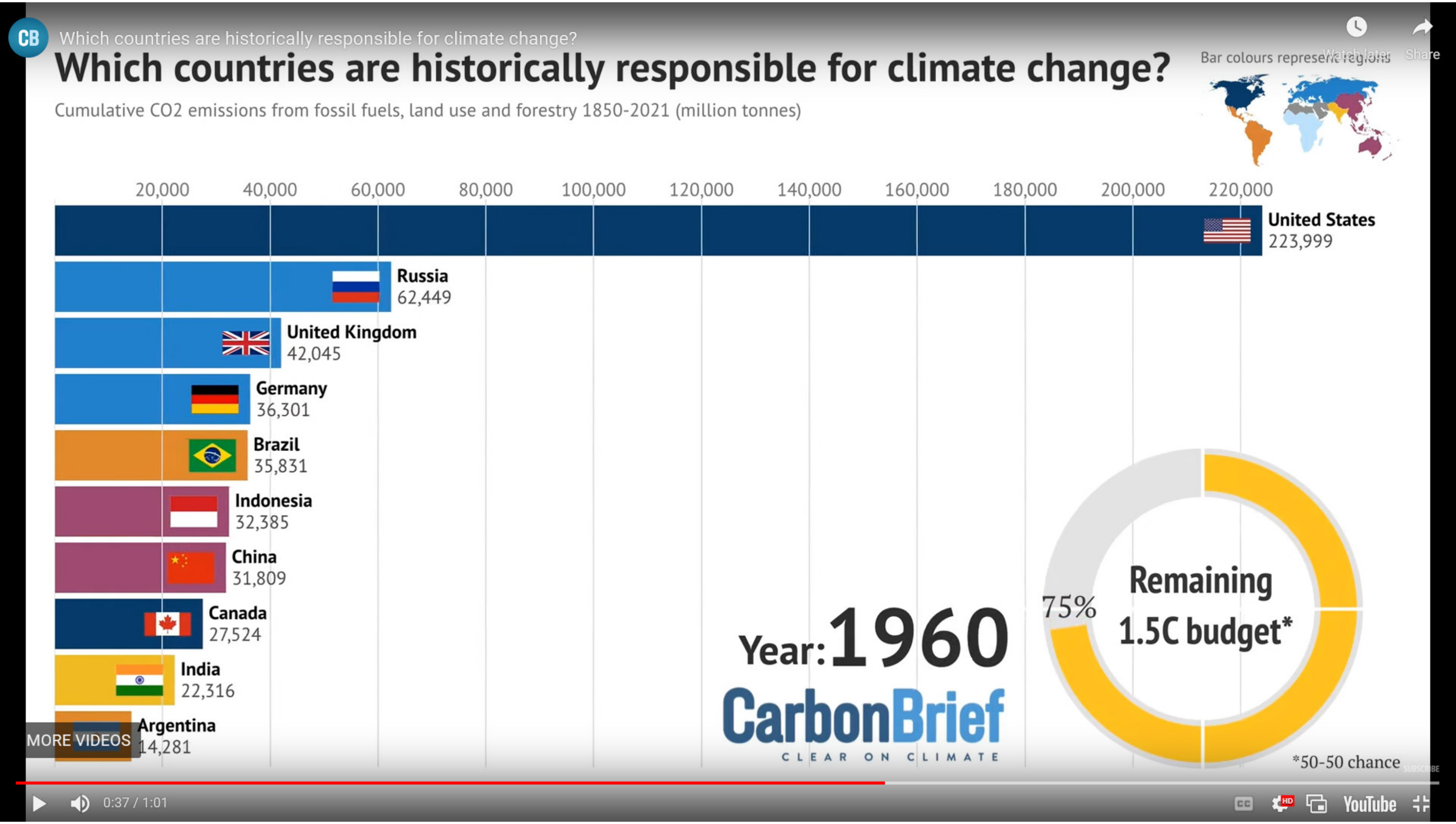




Carbon Emission 1950 to 2019
World
USA
China
India
World minus USA, China, and India
Emission (Gt C yr^{-1})
10
8
6
4
2
0
1950
1960
1970
1980
1990
2000
2010
2020

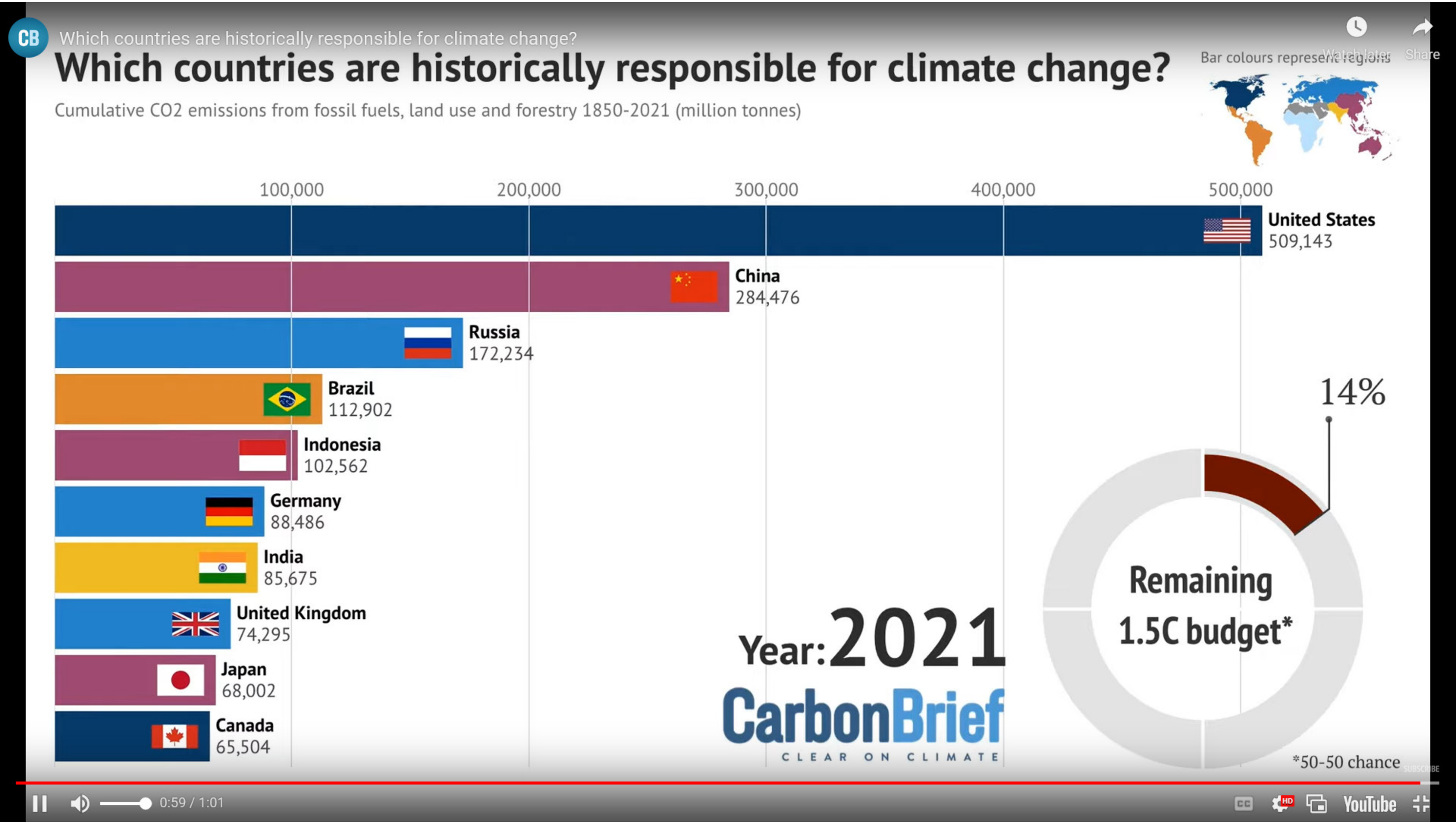

Per-Capita Carbon Emission 1950 to 2019
World
USA
China
India
World minus USA, China, and India
Emission (t C ppy)
0
2
4
6
8
10
1950
1960
1970
1980
1990
2000
2010
2020

Fossil Fuel Emission Animation



https://www.carbonbrief.org/analysis-which-countries-are-historically-responsible-for-climate-change

Fossil Fuel Emission Animation



https://www.carbonbrief.org/analysis-which-countries-are-historically-responsible-for-climate-change

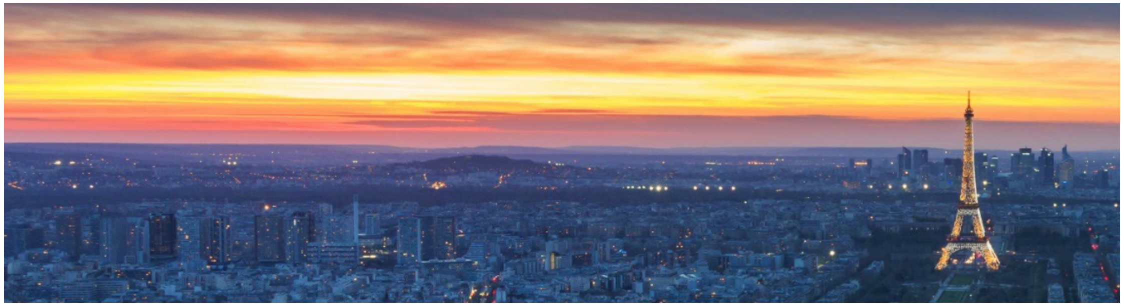
Obama & Xi

US / China Announcement ⇒ Paris Climate Agreement

Nov 2014: Presidents Obama & Xi announced

U.S. would reduce GHG emissions to 27% below 2005 by 2025

China would peak GHG emissions by 2030 with best effort to peak early



Paris Climate Agreement:

Article 2, Section 1, Part a):

Objective to hold "increase in GMST to well below **2°C** above pre-industrial levels and to pursue efforts to limit the temperature increase to **1.5°C** above pre-industrial levels"

NDC: **N**ationally **D**etermined **C**ontributions to reduce GHG emissions

- Submitted prior to Dec 2015 meeting in Paris
- Consist of either **unconditional** (promise) or **conditional** (contingent) pledges
- Generally extend from early 2016 to year 2030

Global Carbon Cycle

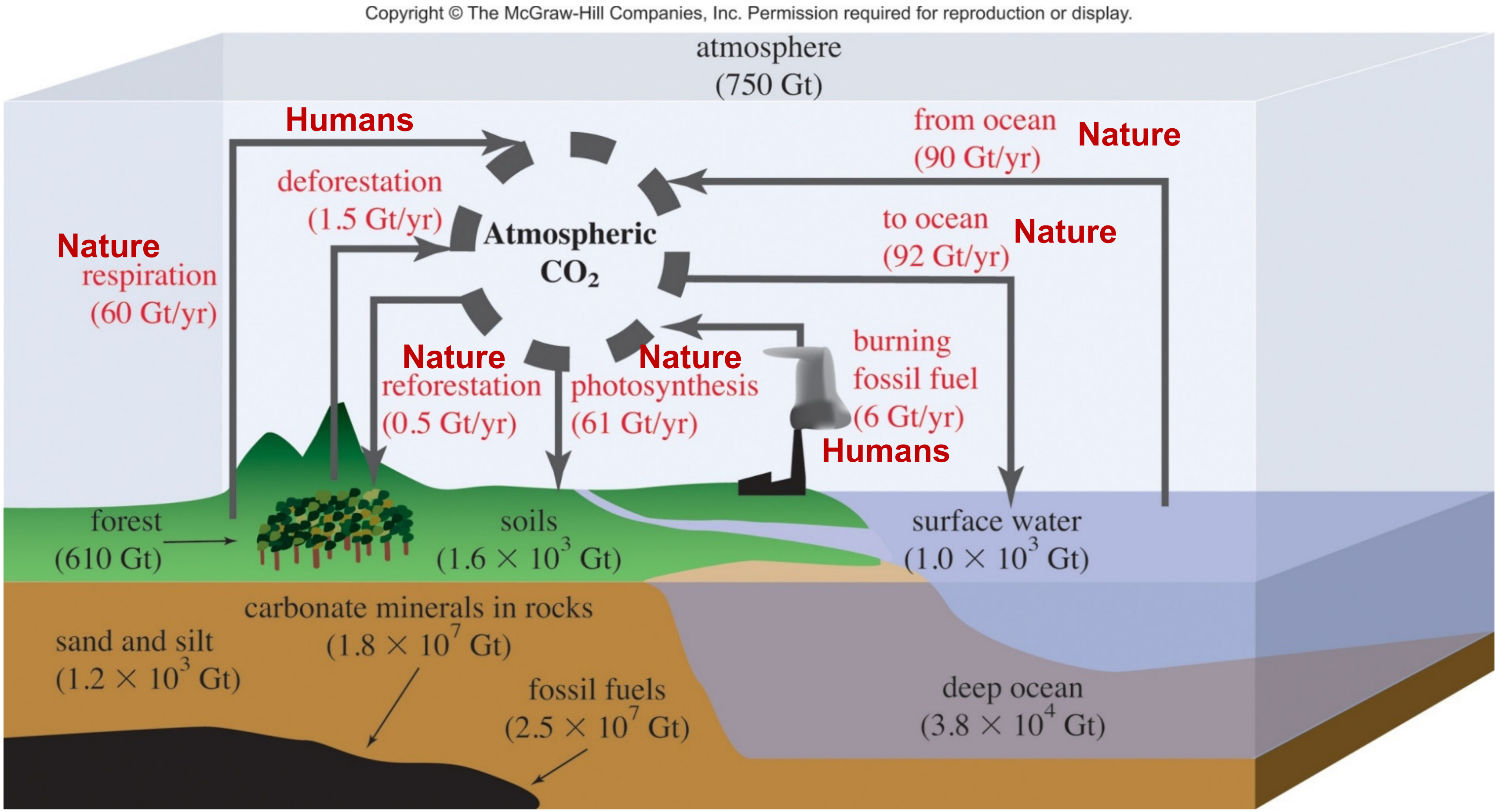


Fig 3.20, Chemistry in Context

CC:

Land Sink = (61 + 0.5) – (60) Gt C / yr = 1.5 Gt C / yr
Ocean Sink = 92 – 90 Gt C / yr = 2 Gt C / yr

In other words, ~3.5 Gt C / yr out of 7.5 Gt C / yr from burning fossil fuel & deforestation was being absorbed by world's oceans & terrestrial biosphere.

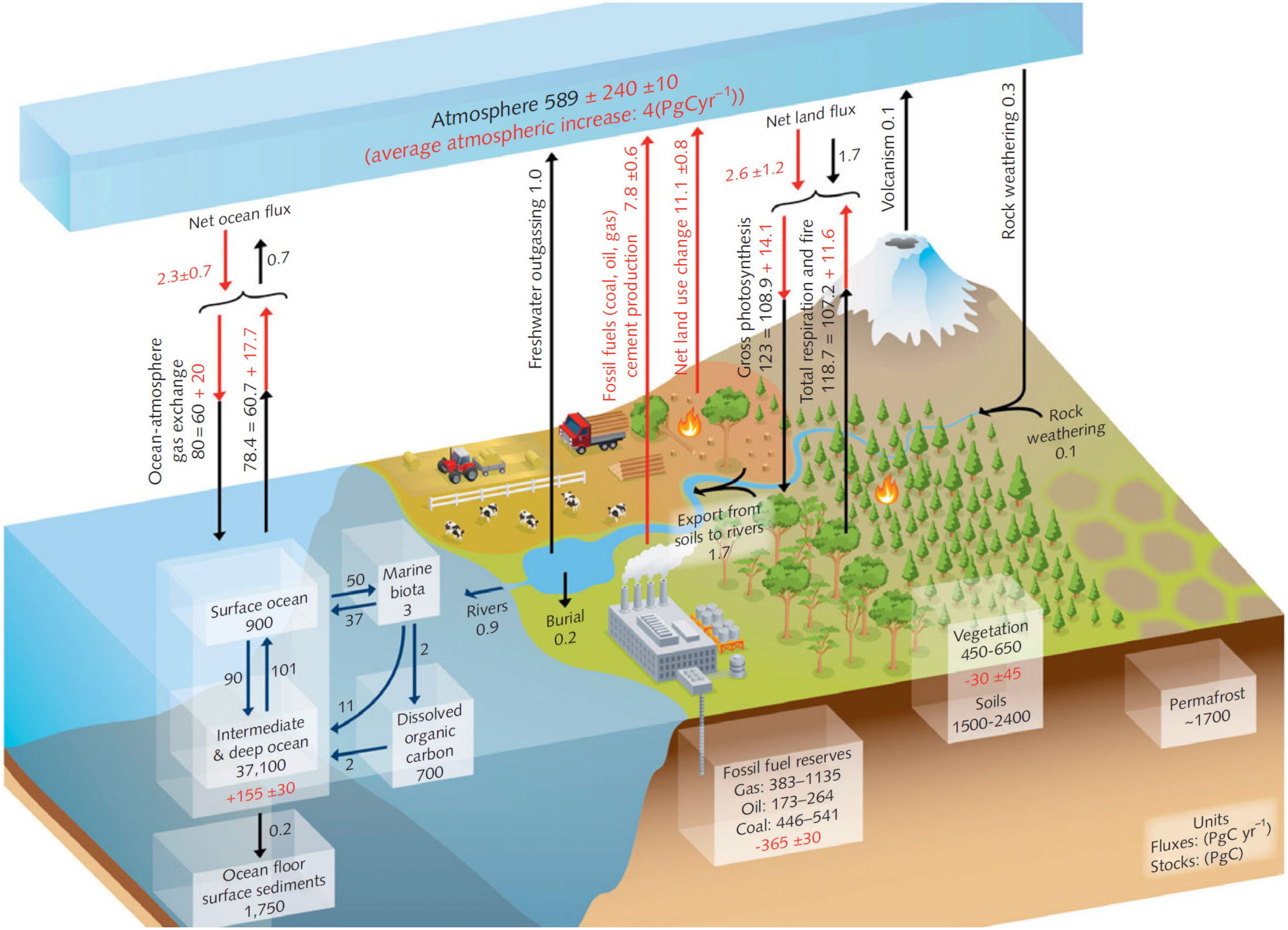


Fig 3.1, Houghton

Houghton:

Land Sink = 2.6 ± 1.2 Gt C / yr

Ocean Sink = 2.3 ± 0.7 Gt C / yr

In other words, ~4.9 Gt C / yr out of 7.8 + 1.1 = 8.9 Gt C / yr from burning fossil fuel & deforestation was being absorbed by world's oceans & terrestrial biosphere for the time period of this figure, which is 2000 to 2009

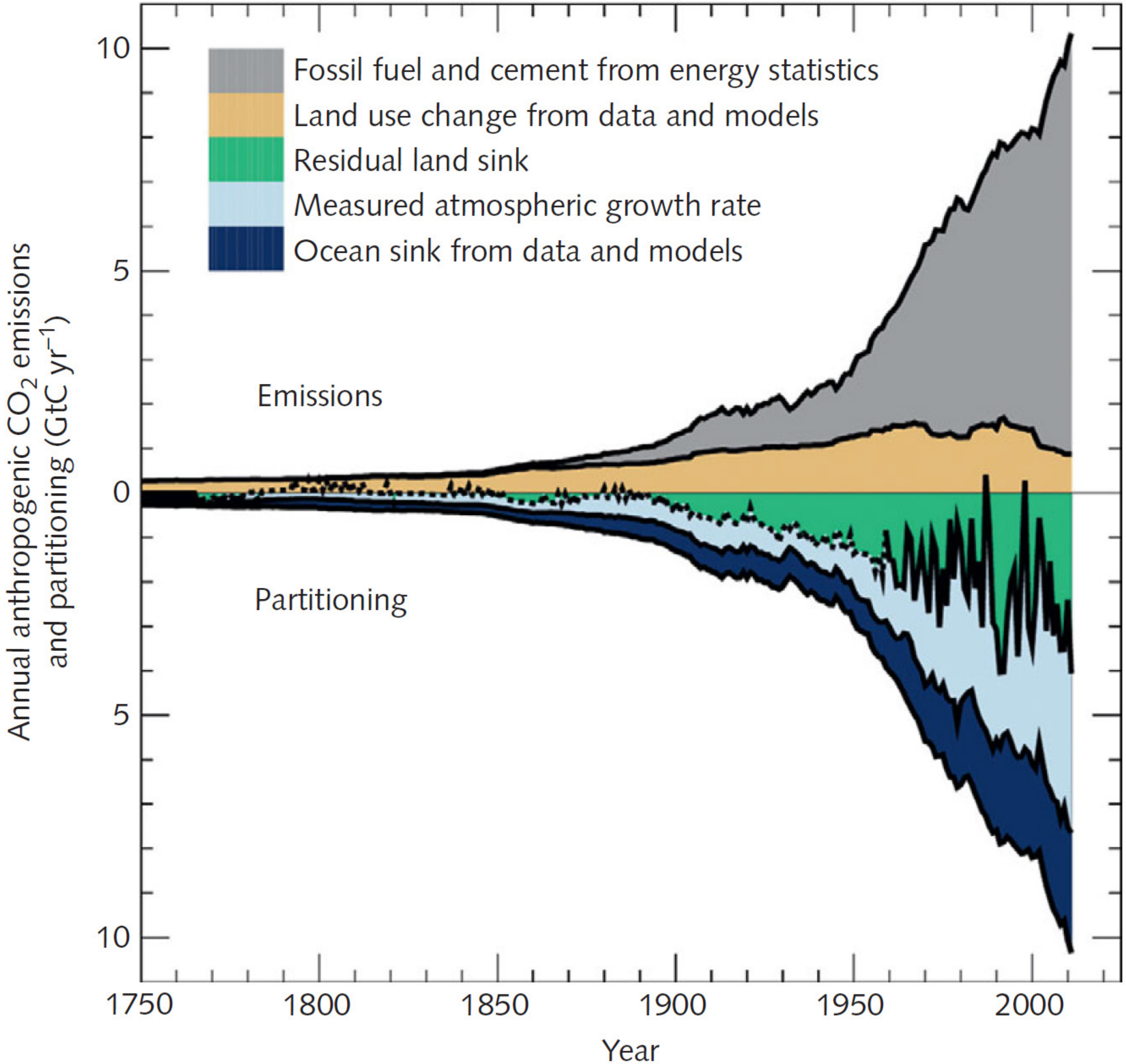
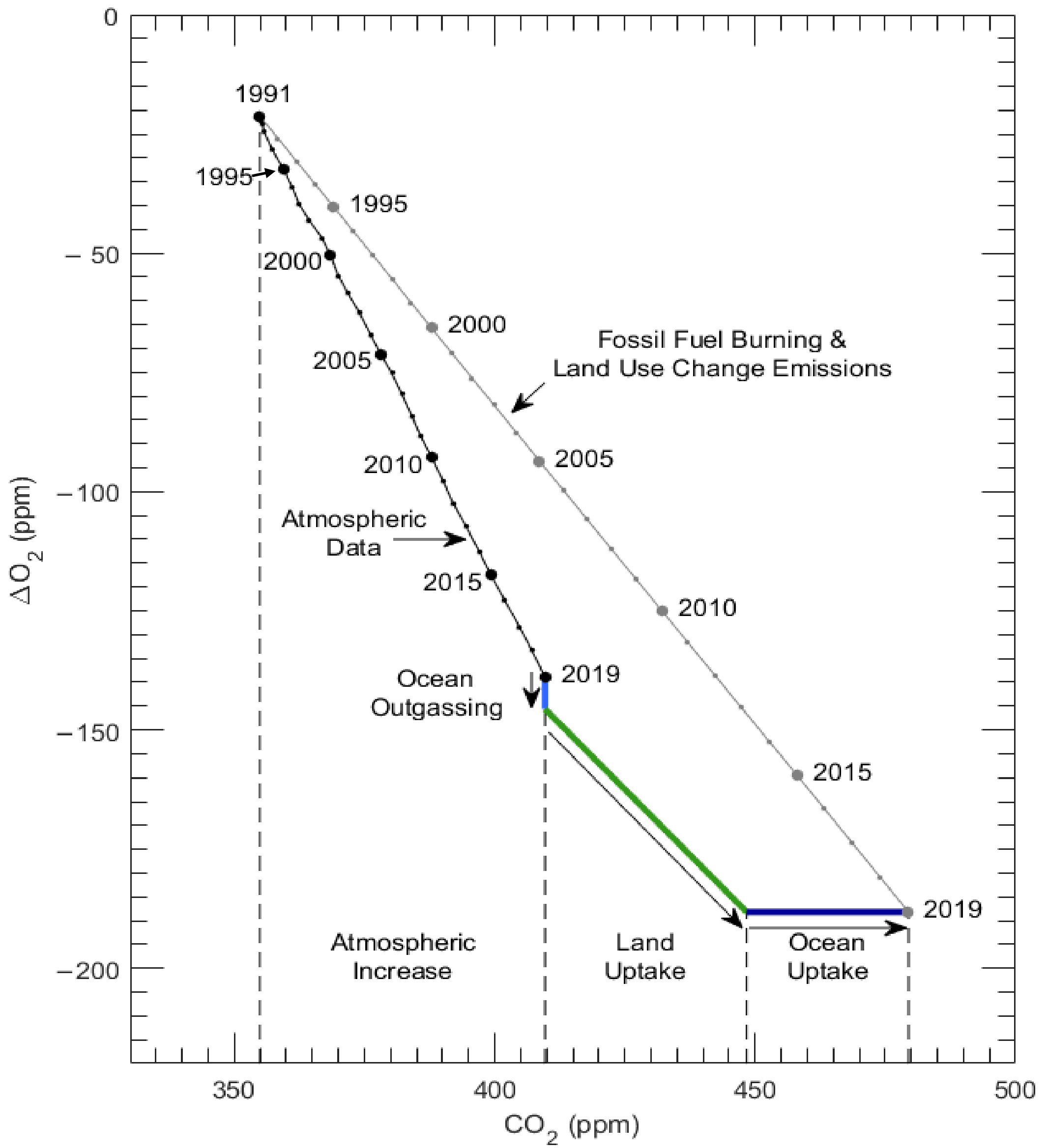


Fig 3.3, Houghton

Inferring CO_2 Uptake Based on ΔO_2

Figure courtesy
Brian Bennett



Uptake of Atmospheric CO_2 by Trees (Land Sink)

Land sink: relatively short lived reservoir

- In this model, future water stress due to climate change eventually limits plant growth
- Feedbacks between climate change & plants could lead to almost 100 ppm additional CO_2 by end of century

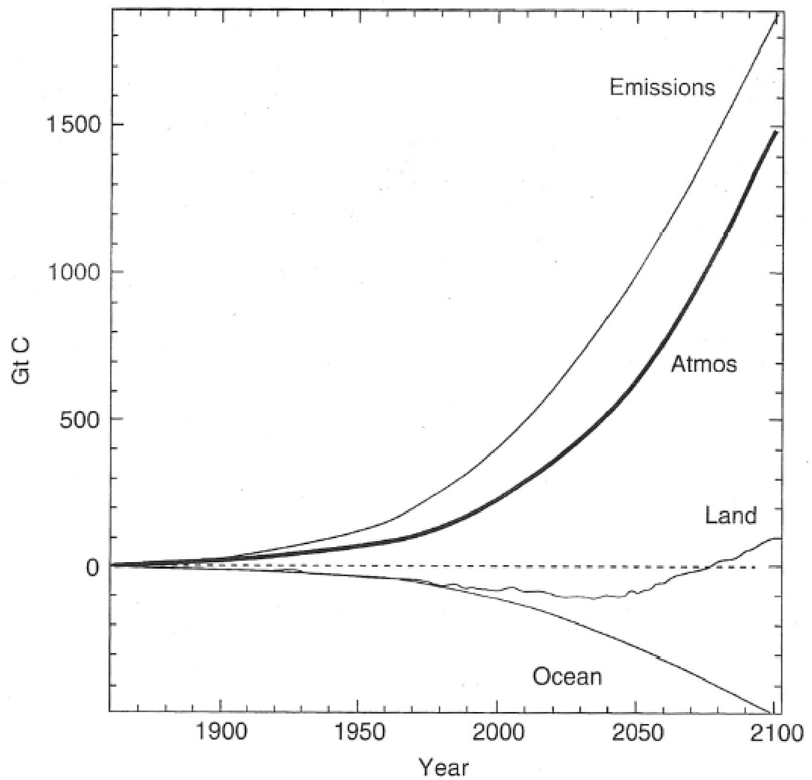
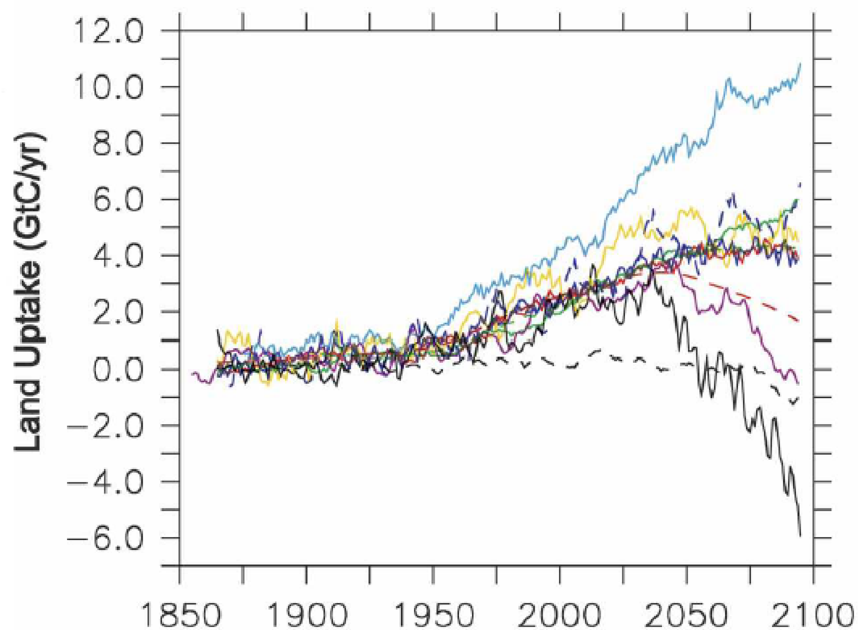


Figure 3.5 Illustrating the possible effects of climate feedbacks on the carbon cycle. Results are shown of the changing budgets of carbon

Figure 3.5, Houghton 3d Edition

- Future fate of land sink highly uncertain according to **11** coupled climate-carbon cycle models examined by Friedlingstein et al. (2006)



Uptake of Atmospheric CO_2 by Trees (Land Sink)

Land sink

As CO_2 ↑, photosynthesis (all things being equal) will increase.

Known as the **"CO_2 fertilizer" effect**

The carbon dioxide fertilisation effect is an example of a biological feedback process. It is a negative feedback because, as carbon dioxide increases, it tends to increase the uptake of carbon dioxide by plants and therefore reduce the amount in the atmosphere, decreasing the rate of global warming.

Page 43, Houghton

Uptake of Atmospheric CO_2 by Trees (Land Sink)

Land sink

As CO_2 ↑, photosynthesis (all things being equal) will increase.

Known as the **"CO_2 fertilizer" effect**

Difficult to quantify empirically in a greenhouse setting because ?

The results of this study suggest that competition for light was the major factor influencing community composition, and that CO_2 influenced competitive outcome largely through its effects on canopy architecture. Early in the experiment competition for nutrients was intense.

Fakhri A. Bazzaz, 1990: https://www.jstor.org/stable/pdf/2097022.pdf

Many Free-Air Carbon dioxide Enrichment (FACE) experiments have been developed, throughout the world including a new experiment in Brazil, to attempt to understand how the terrestrial biosphere will respond to rising levels of atmospheric CO_2

http://aspenface.mtu.edu

https://www.nature.com/news/polopoly_fs/1.12855!/menu/main/topColumns/topLeftColumn/pdf/496405a.pdf?origin=ppub

https://www.nature.com/scitable/knowledge/library/effects-of-rising-atmospheric-concentrations-of-carbon-13254108

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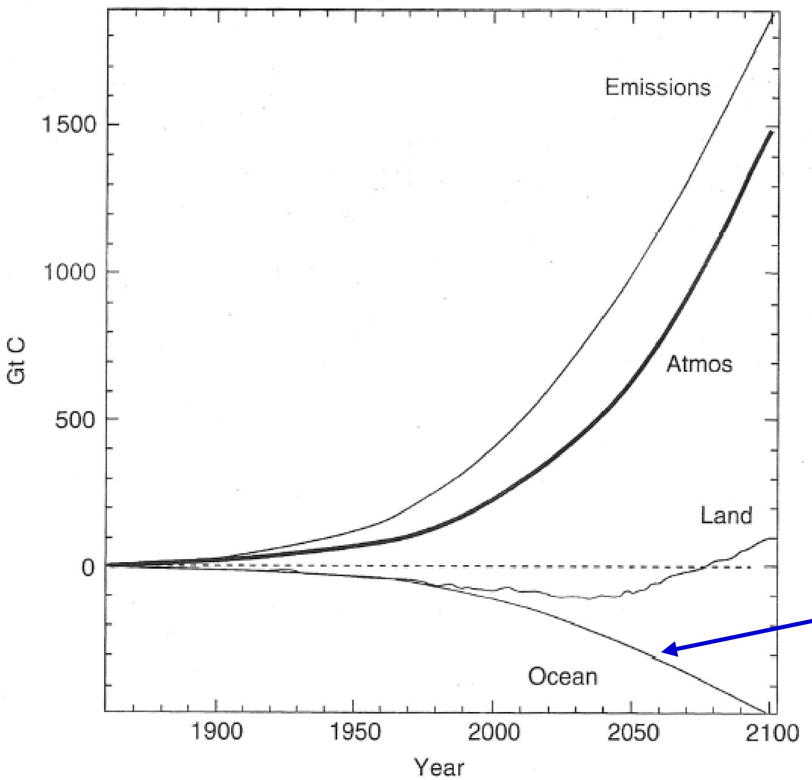


Figure 3.5 Illustrating the possible effects of climate feedbacks on the carbon cycle. Results are shown of the changing budgets of carbon

Ocean sink: relatively long lived reservoir

In nearly all models, ocean uptake slows relative to rise in atmospheric CO_2

Figure 3.5, older (Third) edition of Houghton

Uptake of Atmospheric CO_2 by Oceans

When CO_2 dissolves:

Net: $\mathbf{CO_2(aq) + CO_3^{2-} + H_2O \rightarrow 2\ HCO_3^-}$

Atmospheric CO_2	280 ppm Pre-Industrial	411 ppm Present Day	560 ppm 2 × Pre-Indus.
Ocean Carbon	2020×10^{-6} M	2079×10^{-6} M	2122×10^{-6} M
$[HCO_3^-]$	1771×10^{-6} M	1882×10^{-6} M	1958×10^{-6} M
$[CO_2\ (aq)]$	9.13×10^{-6} M	13.4×10^{-6} M	18.3×10^{-6} M
$[CO_3^{2-}]$	239×10^{-6} M	148×10^{-6} M	146×10^{-6} M
pH	8.32	8.18	8.06

Ocean Carbon $[\Sigma\ CO_2] = [CO_2(aq)] + [HCO_3^-] + [CO_3^{2-}]$

Notes:

$T = 293$ K; Alkalinity= 2.25×10^{-3} M

M ≡ mol/liter

Mathematics supporting this calculation on Extra Slides 1 to 3 of Class Notes.

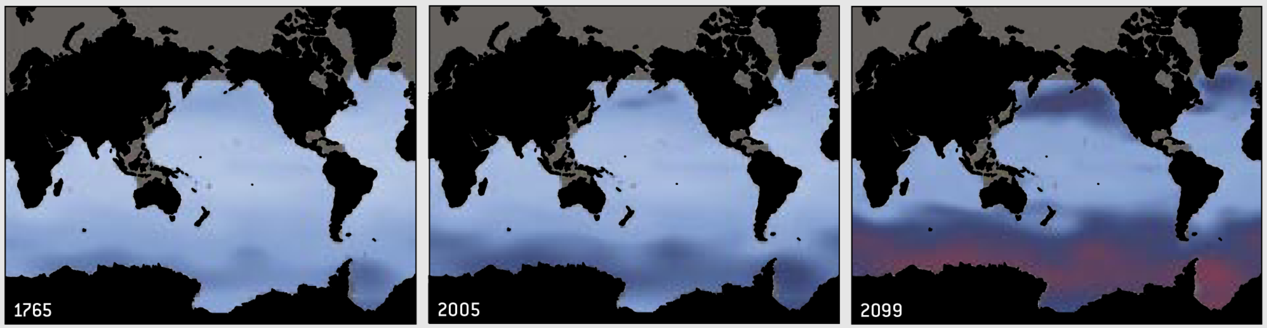
Uptake of Atmospheric CO_2 by Oceans

Oceanic uptake of atmospheric CO_2 leads to ***ocean acidification***

Bad news for ocean dwelling organisms that precipitate shells (basic materials)

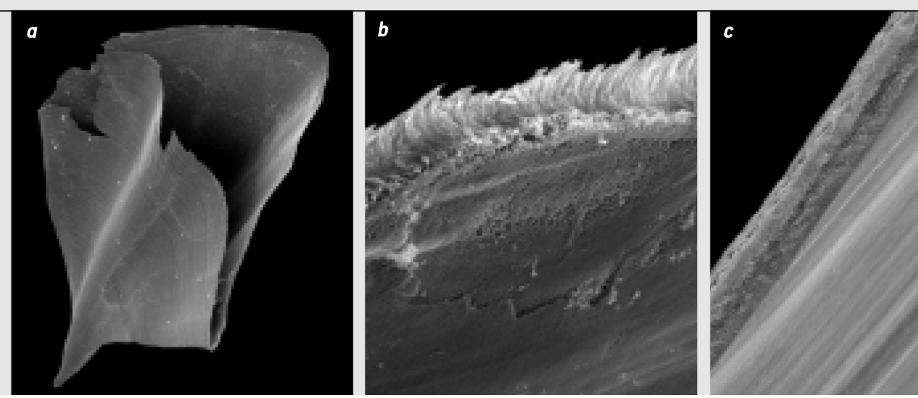
THE (RAGGED) FUTURE OF ARAGONITE

Diminishing pH levels will weaken the ability of certain marine organisms to build their hard parts and will be felt soonest and most severely by those creatures that make those parts of aragonite, the form of calcium carbonate that is most prone to dissolution. The degree of threat will vary regionally.



Before the Industrial Revolution (*left*), most surface waters were substantially "oversaturated" with respect to aragonite (*light blue*), allowing marine organisms to form this mineral readily. But now (*center*), polar surface waters are only marginally oversaturated (*dark blue*). At the end of this century (*right*), such chilly waters, particularly those surrounding Antarctica, are expected to become undersaturated (*purple*), making it difficult for organisms to make aragonite and causing aragonite already formed to dissolve.

Pteropods form a key link in the food chain throughout the Southern Ocean. For these animals (and creatures that depend on them), the coming changes may be disastrous, as the images at the right suggest. The shell of a pteropod kept for 48 hours in water undersaturated with respect to aragonite shows corrosion on the surface (*a*), seen most clearly at high magnification (*b*). The shell of a normal pteropod shows no dissolution (*c*).



Doney, The Dangers of Ocean Acidification, *Scientific American*, March, 2006

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pH	8.32	8.18	8.06

Revelle Factor:

$$\frac{\Delta \text{Atmos}_{CO2}}{\langle \text{Atmos}_{CO2} \rangle_{AVERAGE}} = \frac{131 \text{ ppm}}{0.5 \times (411 + 280) \text{ ppm}} = \mathbf{0.34}$$

$$\frac{\Delta \text{Ocean Carbon}}{\langle \Delta \text{Ocean Carbon} \rangle_{AVERAGE}} = \frac{59 \times 10^{-6} \text{ M}}{0.5 \times (2020 + 2079) \times 10^{-6} \text{ M}} = \mathbf{0.029}$$

Pre-industrial to present: Ocean carbon rose by 2.9% for a 34% increase in atmospheric CO_2

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pH	8.32	8.18	8.06

Revelle Factor:

$$\frac{\Delta \mathrm{Atmos}_{CO2}}{\langle \mathrm{Atmos}_{CO2} \rangle_{AVERAGE}} = \frac{149\ \mathrm{ppm}}{0.5 \times (560 + 411)\ \mathrm{ppm}} = \mathbf{0.31}$$

$$\frac{\Delta \mathrm{Ocean\ Carbon}}{\langle \Delta \mathrm{Ocean\ Carbon} \rangle_{AVERAGE}} = \frac{43 \times 10^{-6}\ \mathrm{M}}{0.5 \times (2079 + 2122) \times 10^{-6}\ \mathrm{M}} = \mathbf{0.020}$$

Present to a future we hope to avoid: Ocean carbon will rise by 2.0% for a 31% increase in atmospheric CO_2