

Global Carbon Cycle

AOSC / CHEM 433 & AOSC / CHEM 633

Ross Salawitch

Class Web Sites:

<http://www2.atmos.umd.edu/~rjs/class/spr2022>

<https://myelms.umd.edu/courses/137772>

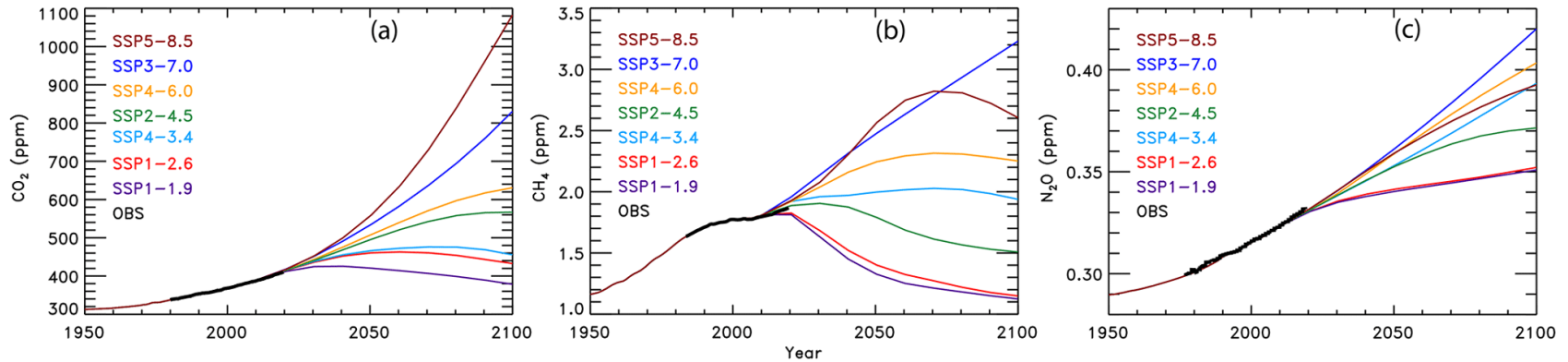
Goals for today:

- Overview of the Global Carbon Cycle “scratching below the surface”
- Ocean and land uptake of CO₂ : past and future
- Policy to reduce emissions of CO₂

Lecture 5

10 February 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 CO₂, CH₄, N₂O, 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

CO₂ is long lived: society must reduce emissions soon or we will be committed to dramatic, future increases in [CO₂]

Curves for which [CO₂] levels off at ~550 ppm or less have emissions peaking NOW !

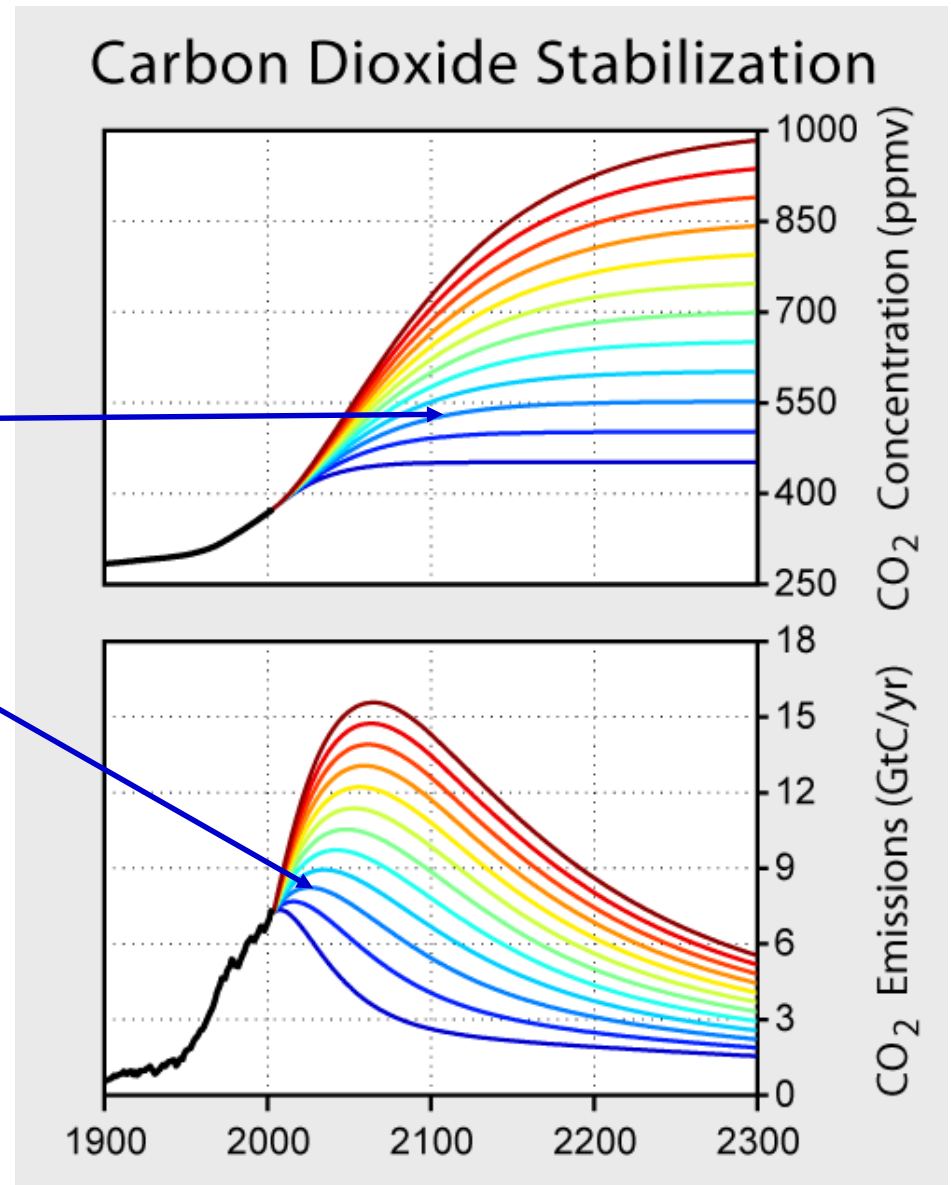
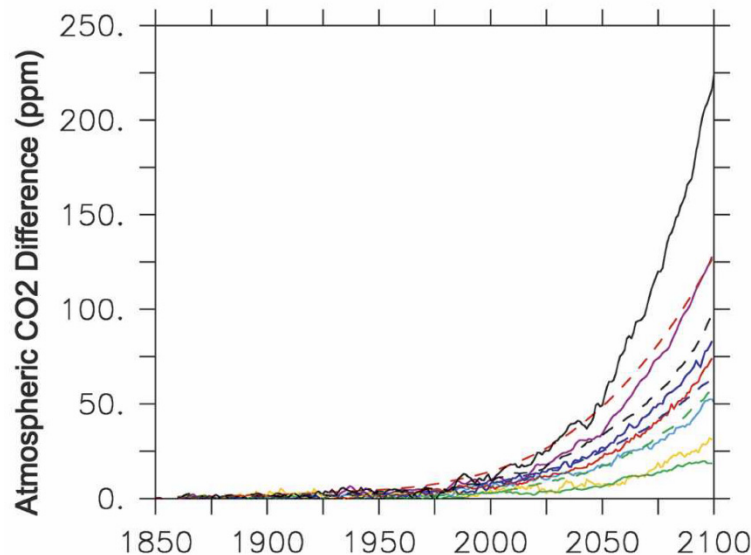
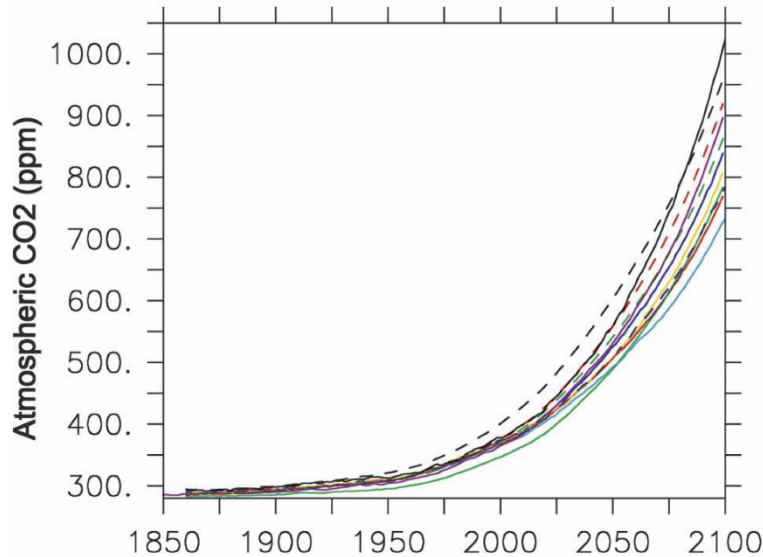


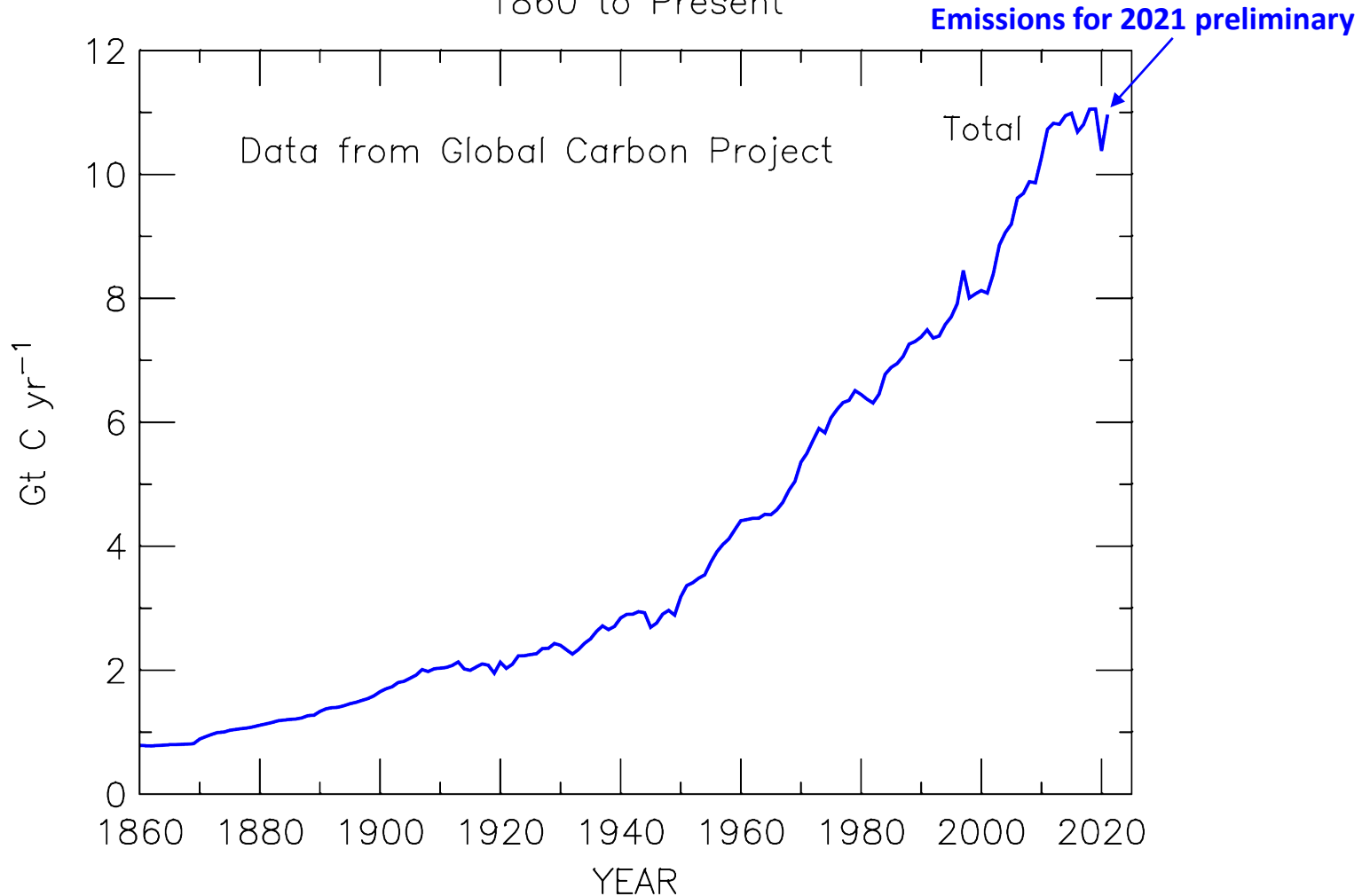
Image: “Global Warming Art” : <http://archive.is/JT5rO>

Motivation 2



- Prior slides examined atmospheric CO₂ from a single model of the global carbon cycle
- Friedlingstein et al. (2006) compared CO₂ from **11** different coupled climate-carbon cycle models, each constrained by the same specified time series of anthropogenic CO₂ emission and found:
 - 1) future climate change will reduce the efficiency of the *Earth system* to absorb the anthropogenic carbon perturbation
 - 2) difference in CO₂ 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!)

Fossil Fuel, Cement, and Land Use Change Emissions
1860 to Present



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 CO₂ Record

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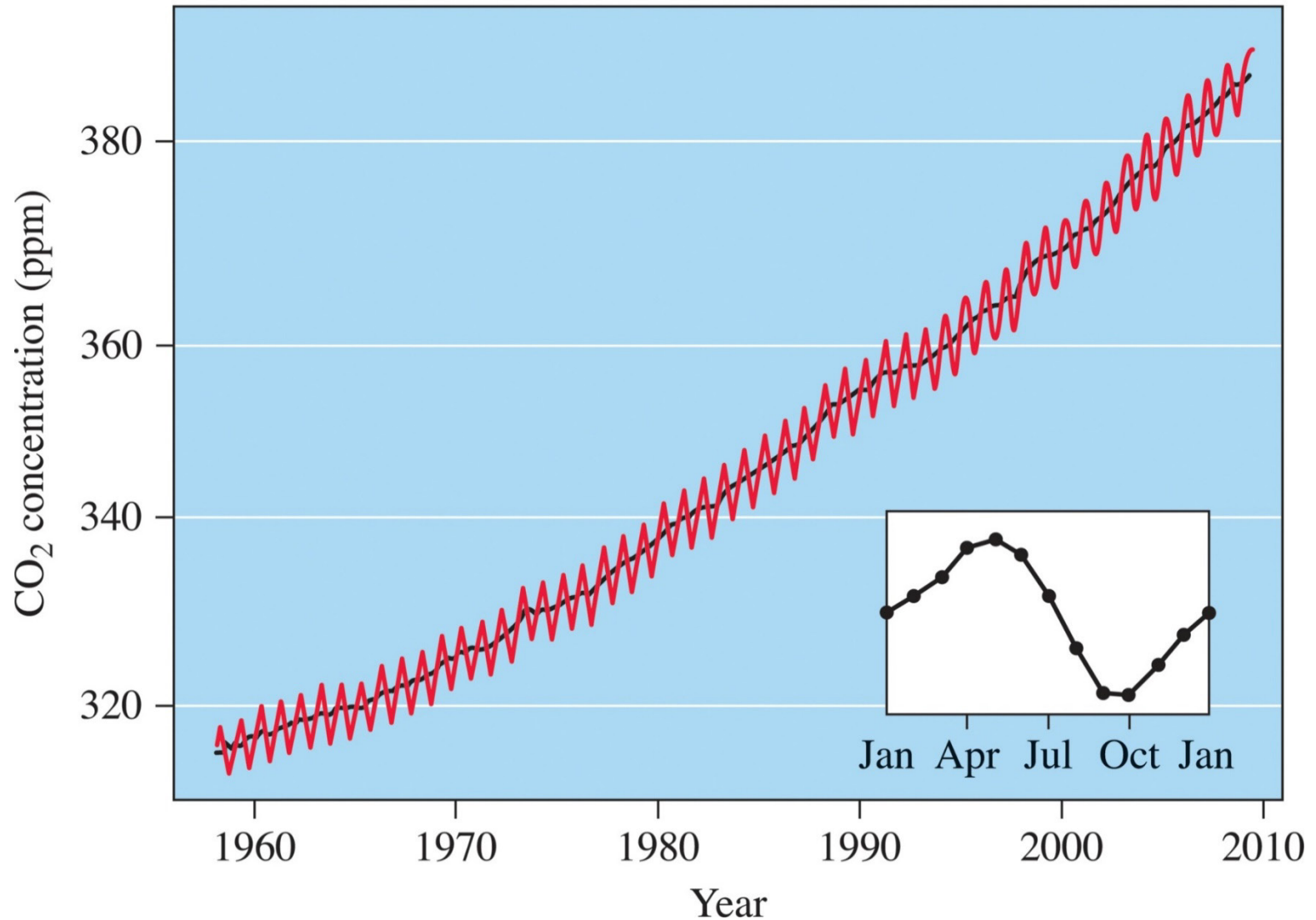


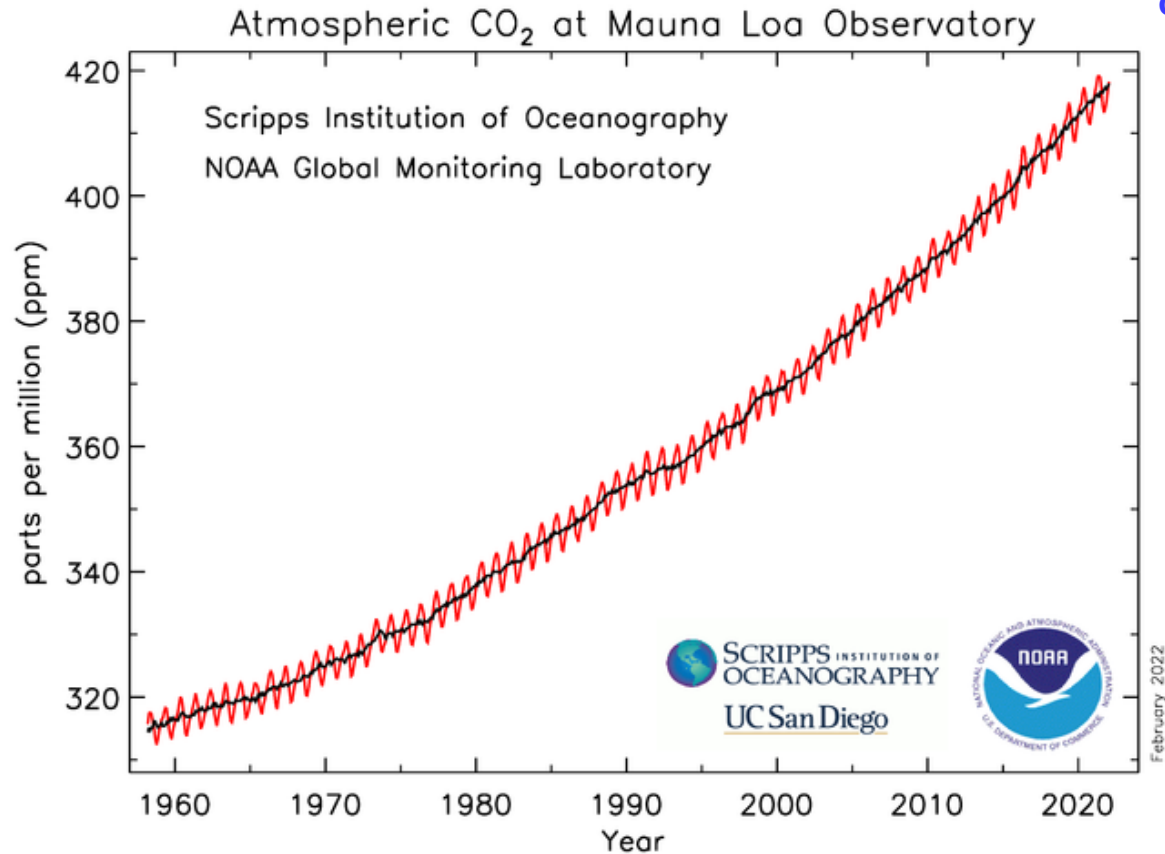
Figure 3.3, Chemistry in Context

Modern CO₂ Record

CO₂ at MLO on 8 Feb 2021: 419.3 parts per million (ppm)

CO₂ at MLO on 8 Feb 2020: 416.0 parts per million (ppm)

$\Delta\text{CO}_2 = 3.3 \text{ ppm}$ per year
or 0.8 % per year



Legacy of Charles Keeling, Scripps Institution of Oceanography, La Jolla, CA

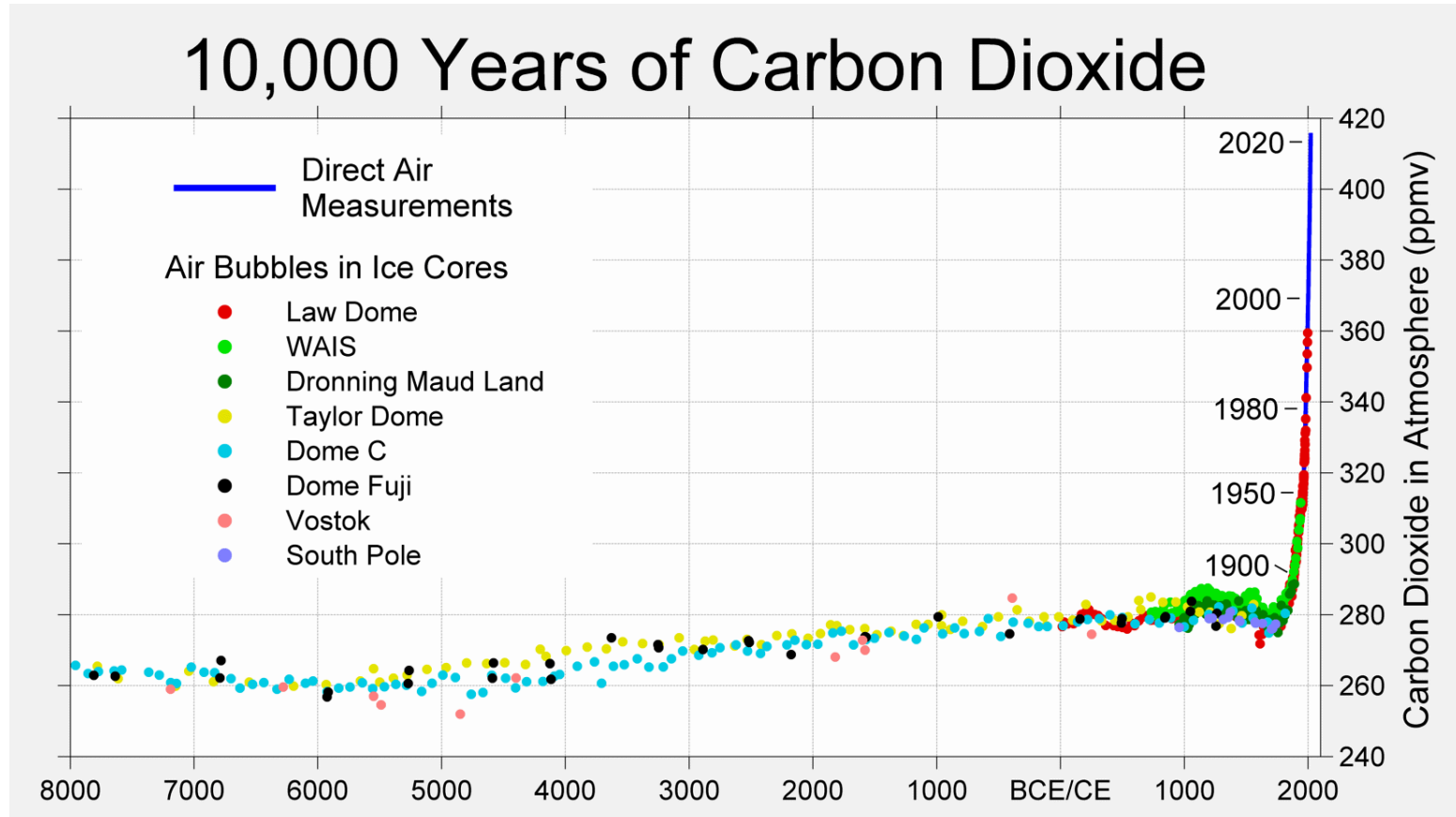
https://www.esrl.noaa.gov/gmd/webdata/ccgg/trends/co2_data_mlo.png

See also <https://www.co2.earth/daily-co2>

Carbon Dioxide (CO₂): The Past Eight Millennium

Combustion:

Gasoline (octane) $2 \text{ C}_8\text{H}_{18} + 25 \text{ O}_2 + \text{Small Source of Energy} \rightarrow 16 \text{ CO}_2 + 18 \text{ H}_2\text{O} + \text{Lots of Energy}$
Natural gas (methane) $\text{CH}_4 + 2 \text{ O}_2 + \text{Small Source of Energy} \rightarrow \text{CO}_2 + 2 \text{ H}_2\text{O} + \text{Lots of Energy}$
Coal $\text{C}_{135}\text{H}_{96}\text{O}_9\text{NS} + 309 \text{ O}_2 + \text{Small Source of Energy} \rightarrow 135 \text{ CO}_2 + 48 \text{ H}_2\text{O} + \text{Lots of Energy} + \text{Other Pollutants}$



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

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

Modern CO₂ Record

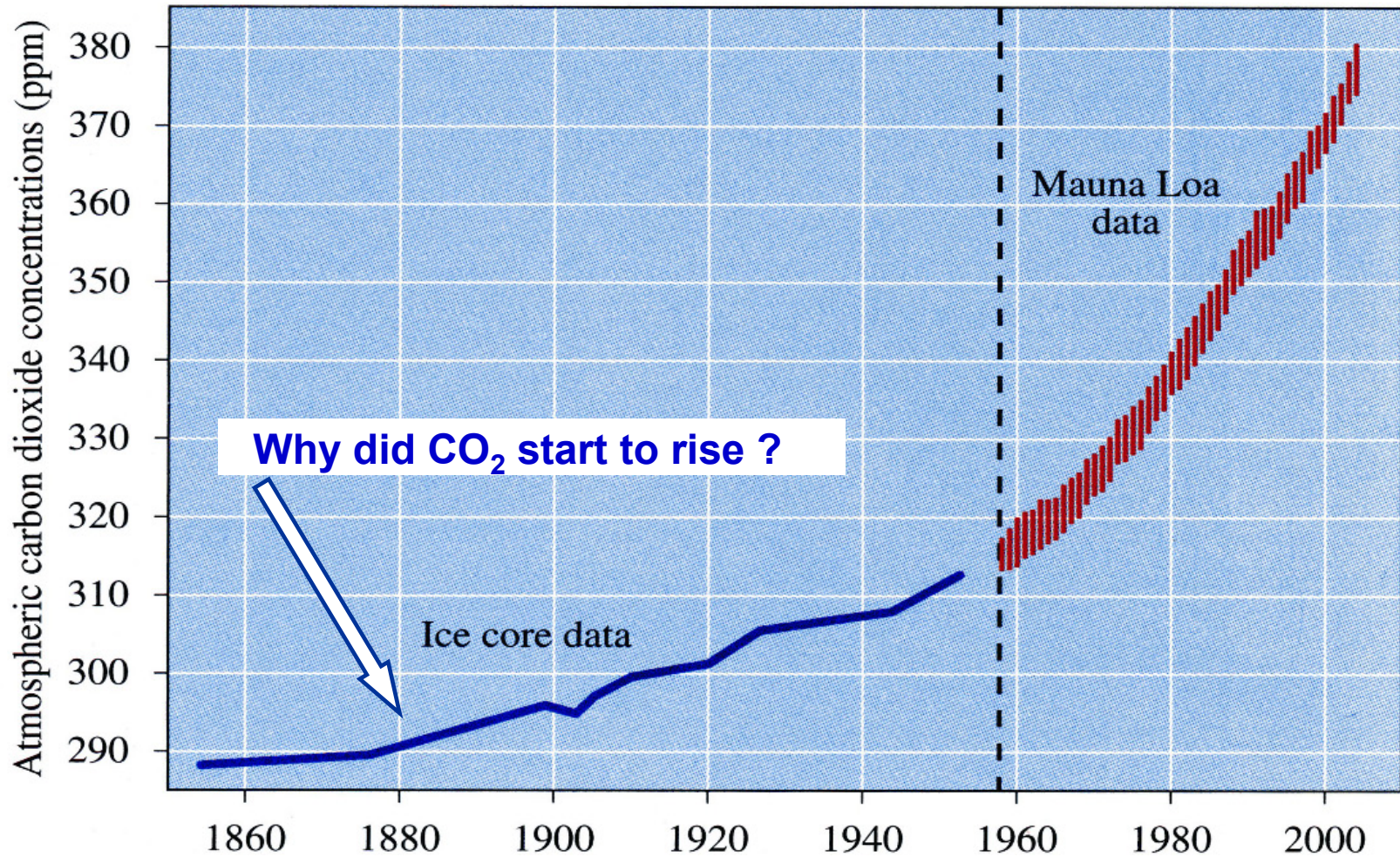
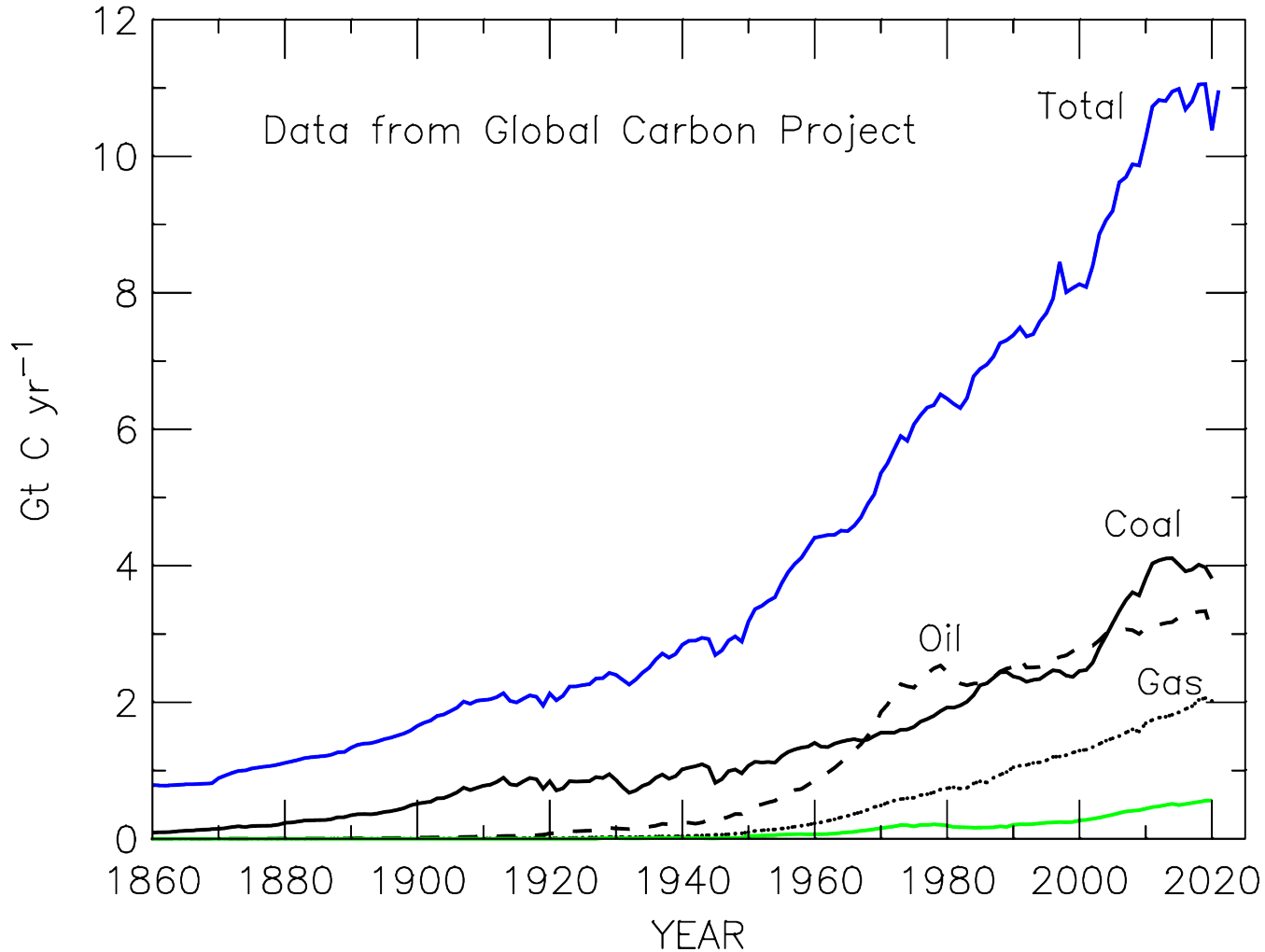


Figure 3.5, *Chemistry in Context*, 7th Edition

Fossil Fuel, Cement, and Land Use Change Emissions 1860 to Present



Human “Fingerprints” on Atmospheric CO₂

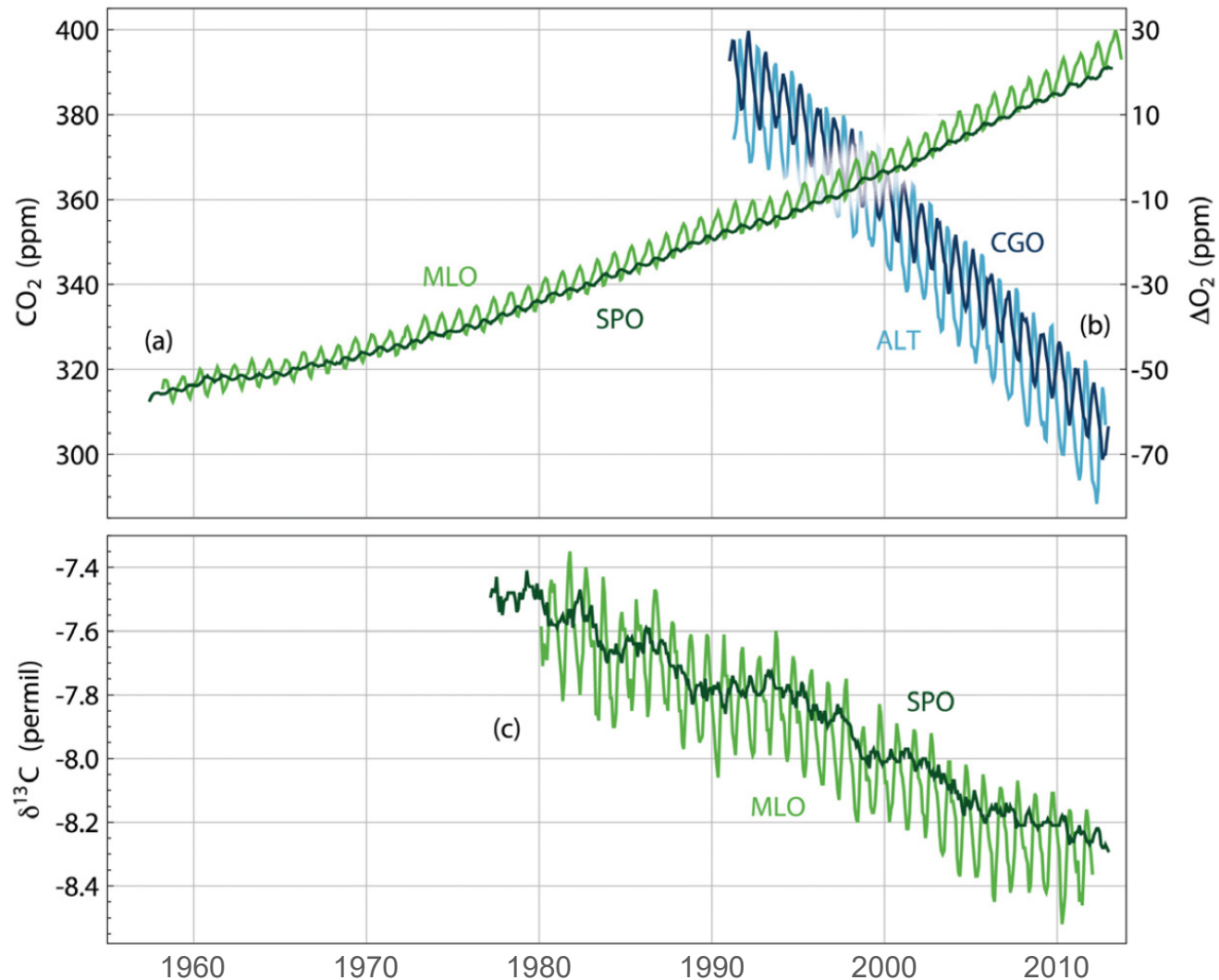
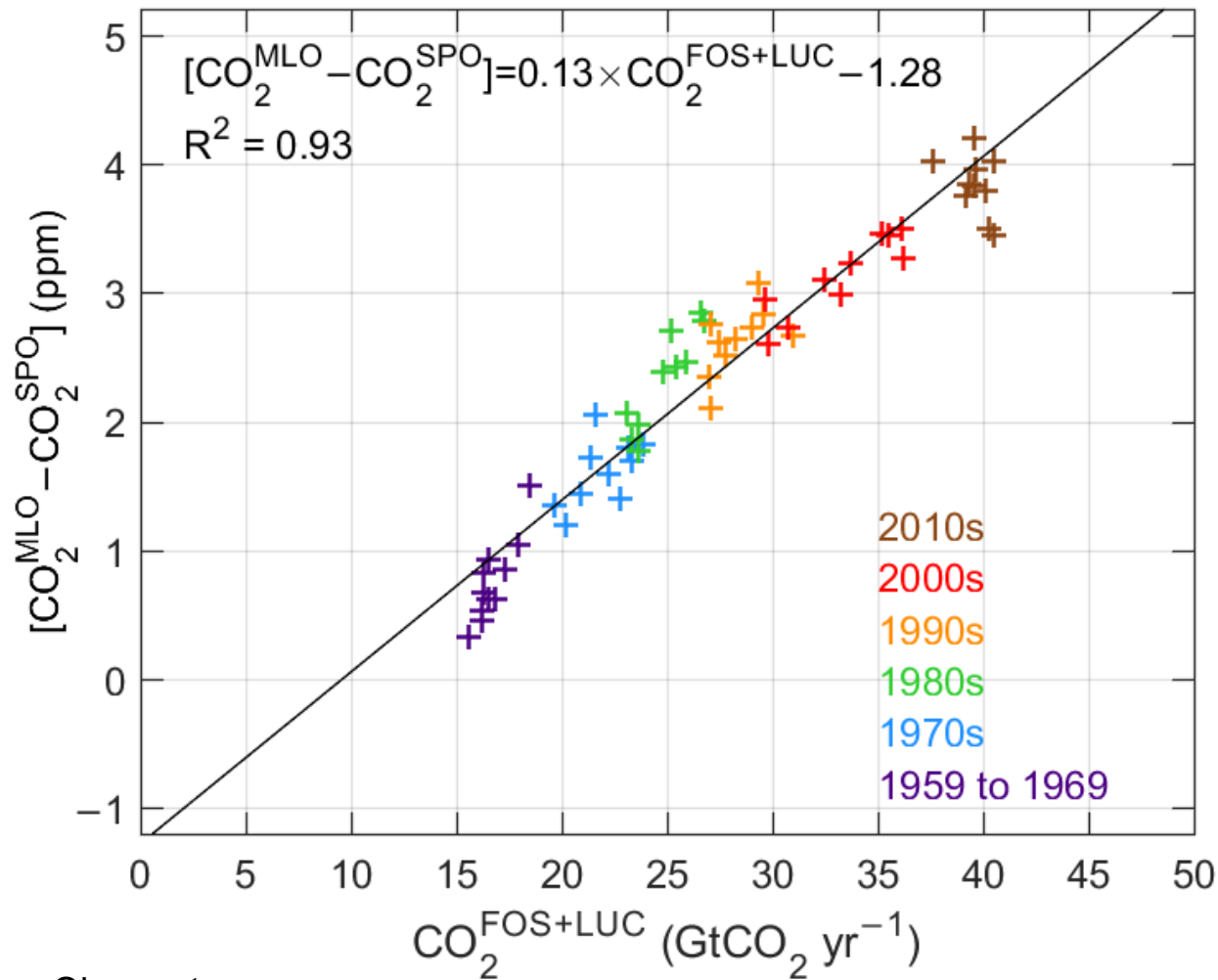


Figure 3.4 Atmospheric concentrations observed at representative stations of (a) carbon dioxide from Mauna Loa (MLO) Northern Hemisphere and South Pole (SPO) Southern Hemisphere; (b) Oxygen from Alert (ALT) Canada, 82°N, and Cape Grim (CGO), Australia, 41°S; (c) ¹³C/¹²C from Mauna Loa (MLO) and South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

Fig 3.4, Houghton

Human “Fingerprints” on Atmospheric CO₂



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*

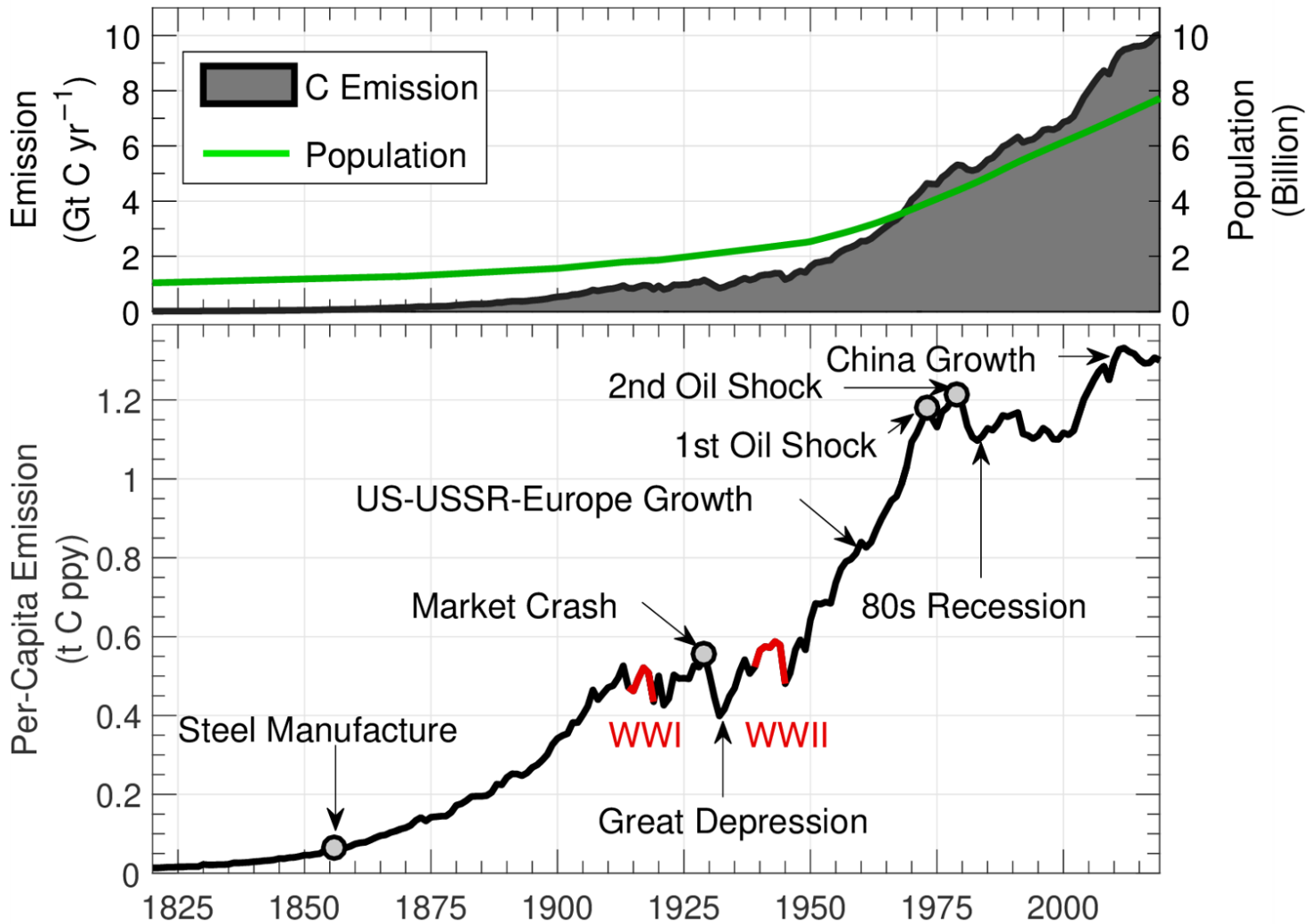
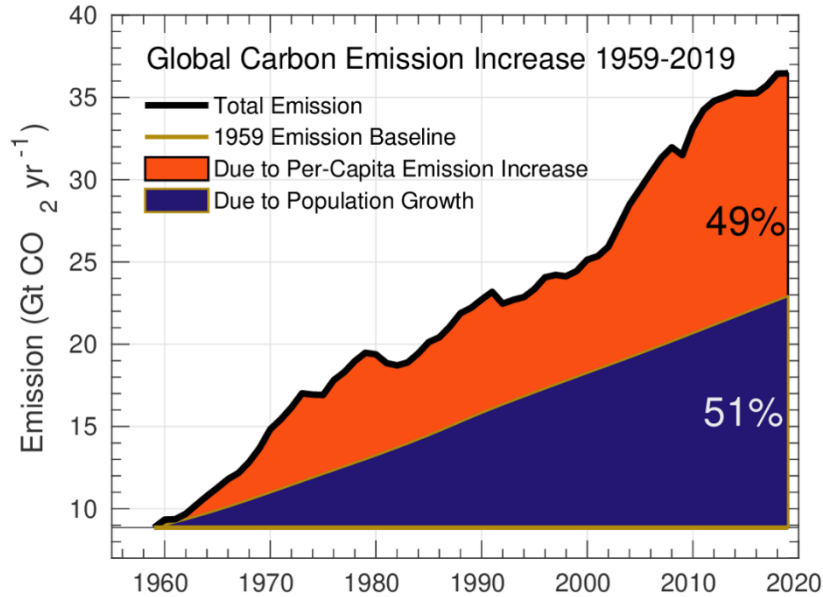


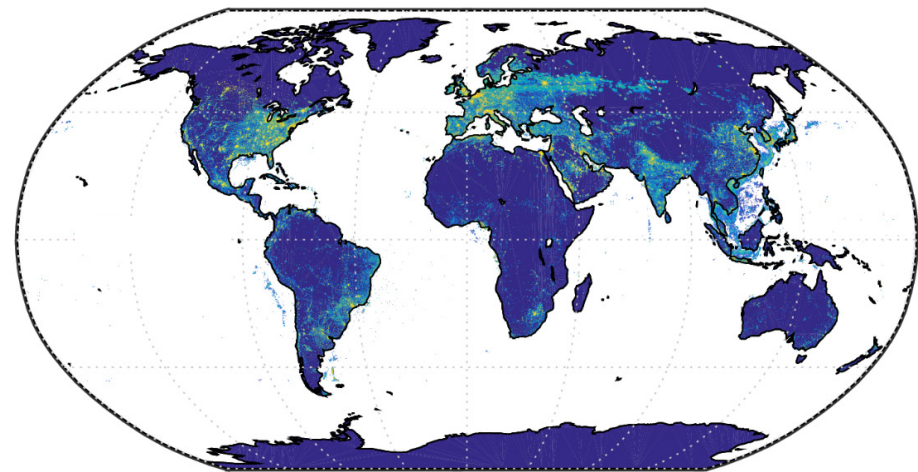
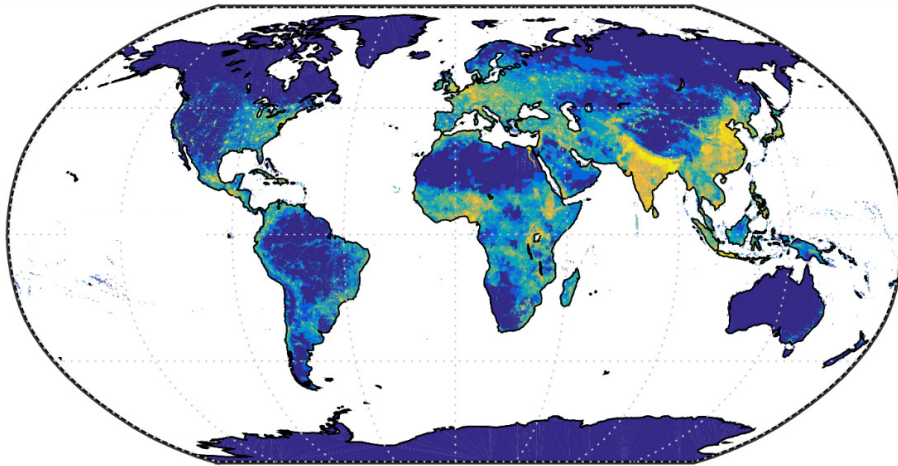
Figure courtesy Walt Tribett

After Fig 3.1 *Paris Beacon of Hope*

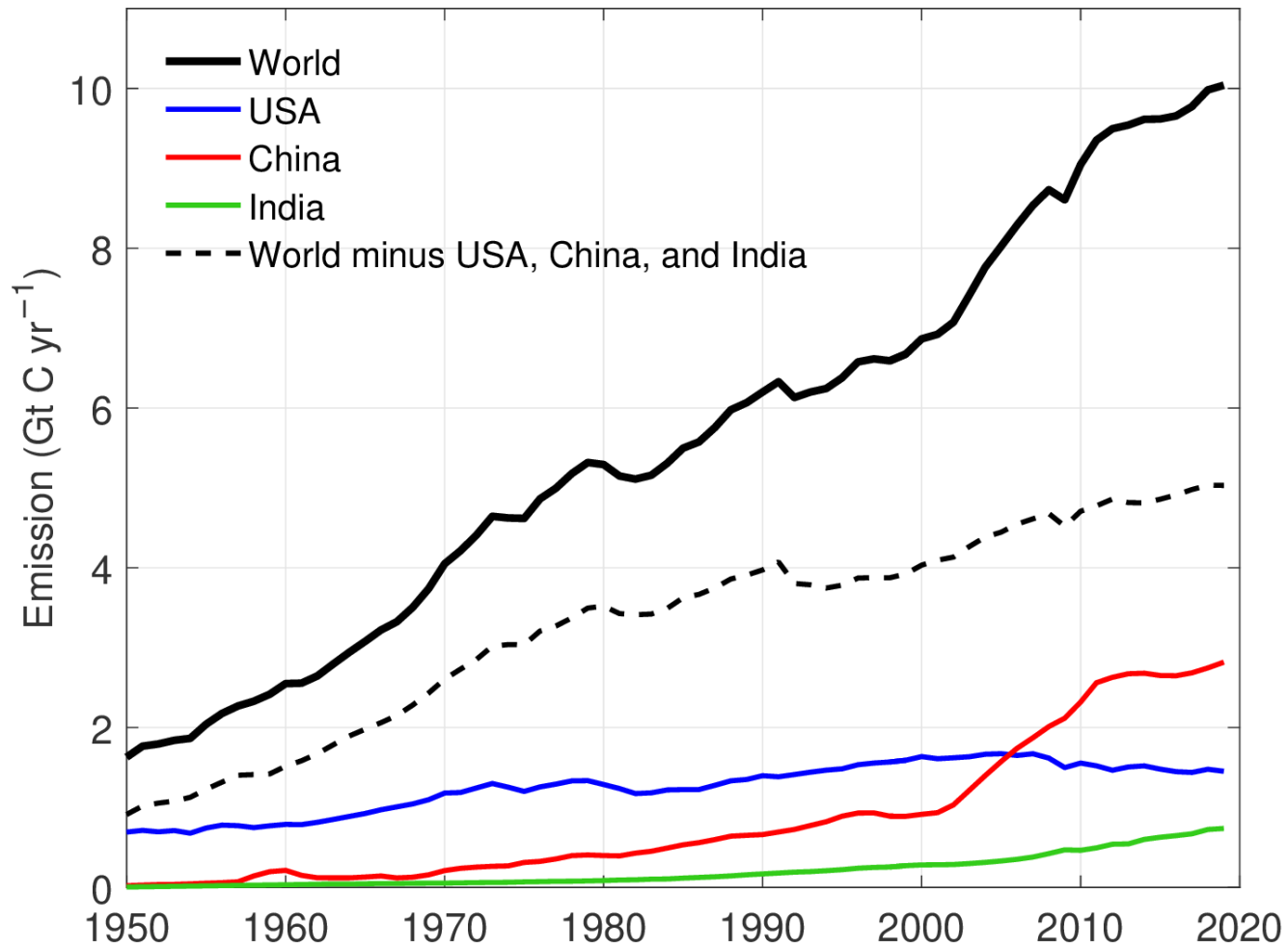
Fossil Fuel Emissions



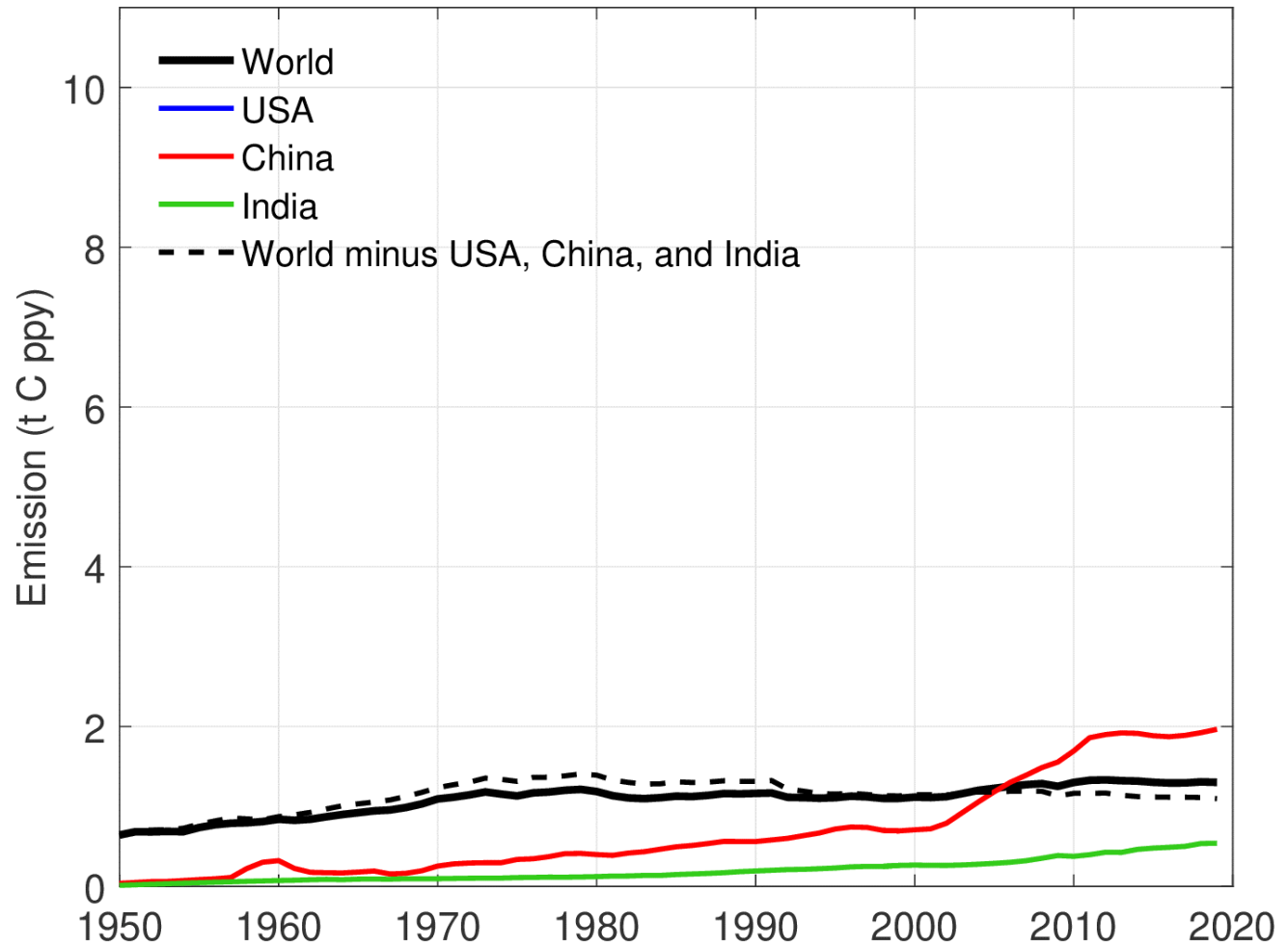
Population increase & **per-capita rise** both contribute, nearly equally to the global rise in C emissions



Carbon Emission 1950 to 2019



Per-Capita Carbon Emission 1950 to 2019



Fossil Fuel Emission Animation

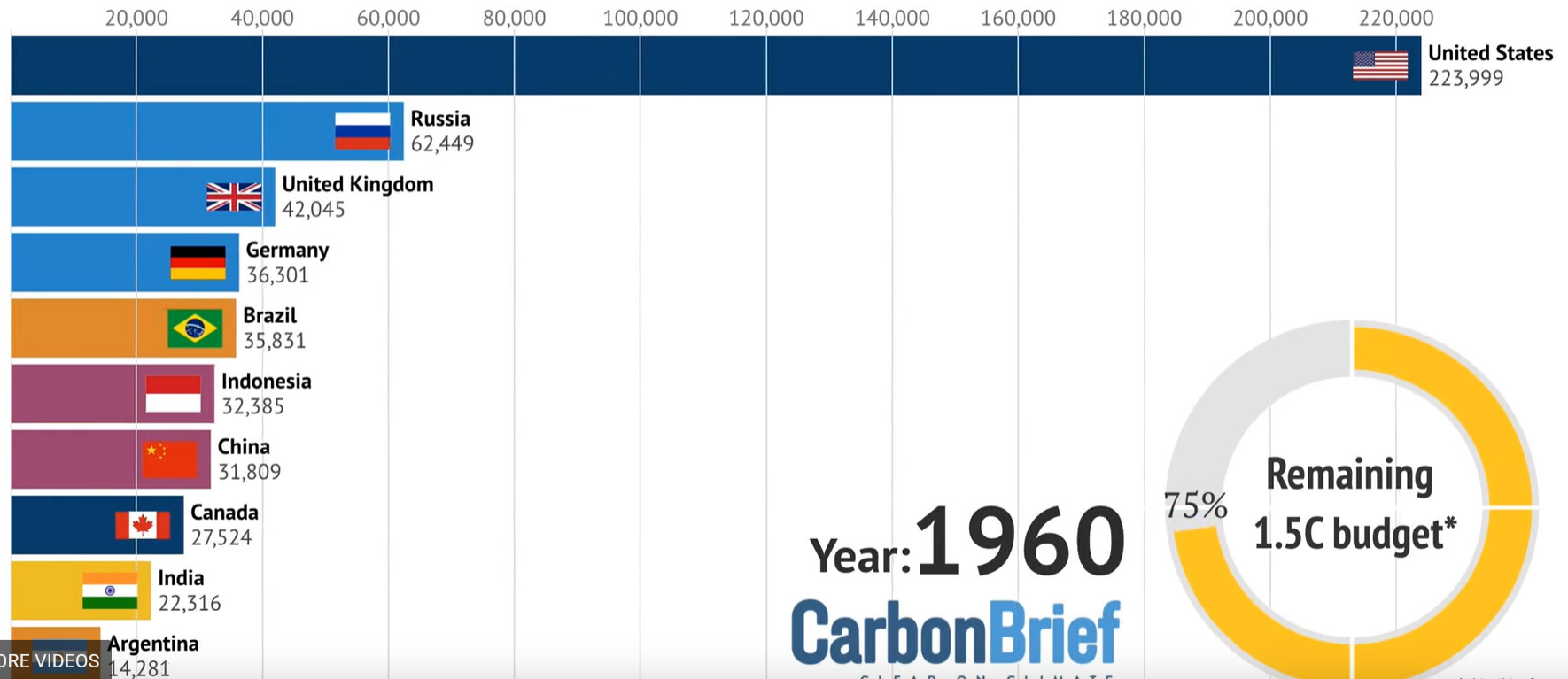
CB

Which countries are historically responsible for climate change?

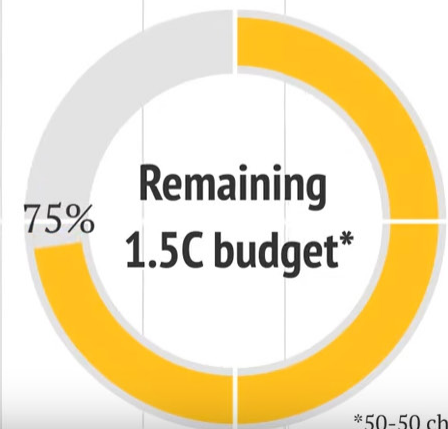
Which countries are historically responsible for climate change?

Cumulative CO2 emissions from fossil fuels, land use and forestry 1850-2021 (million tonnes)

Bar colours represent regions



Year: **1960**
CarbonBrief
CLEAR ON CLIMATE



*50-50 chance

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

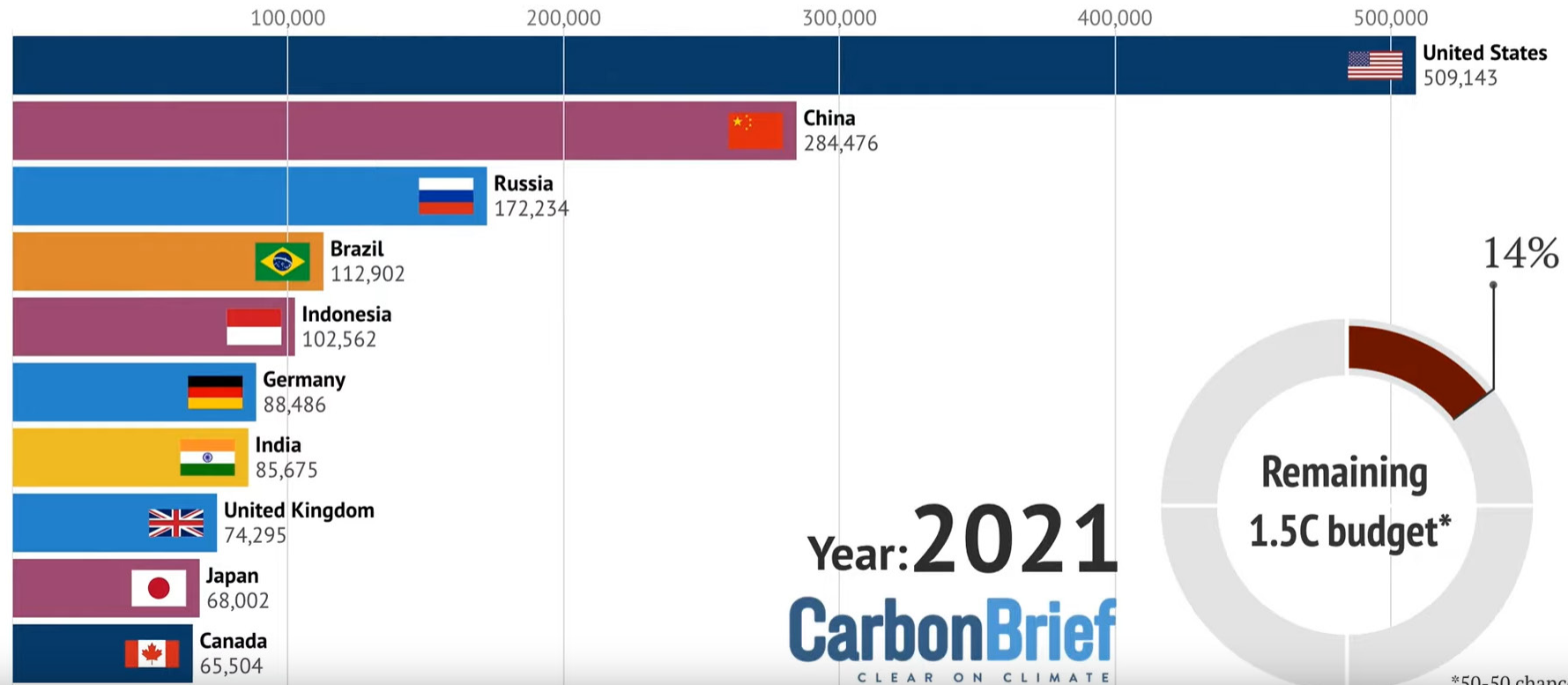
Fossil Fuel Emission Animation

CB

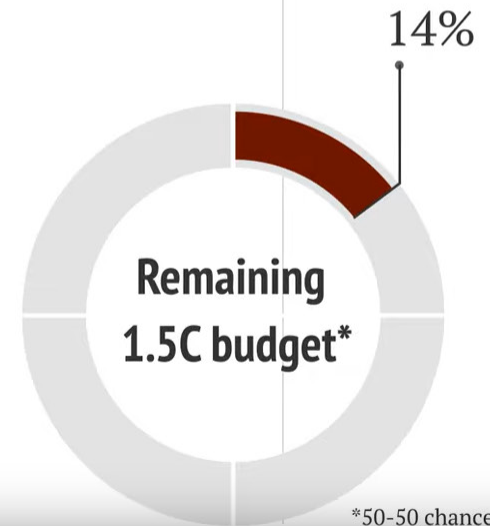
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Cumulative CO2 emissions from fossil fuels, land use and forestry 1850-2021 (million tonnes)



Year: 2021
CarbonBrief
CLEAR ON CLIMATE



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

Obama & Xi

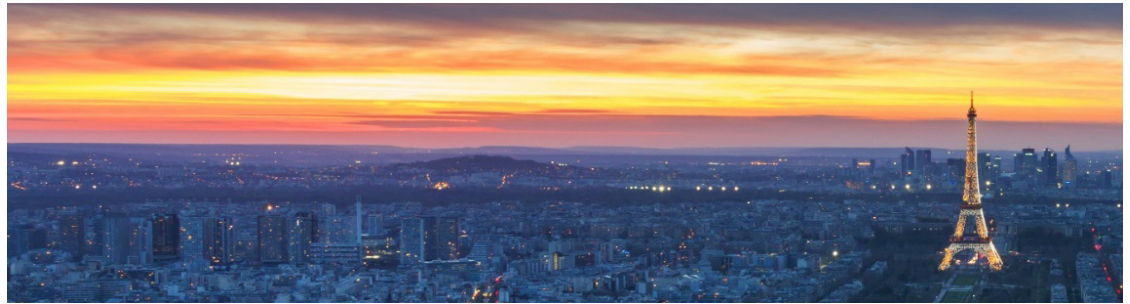
US / China Announcement $\Rightarrow$ Paris Climate Agreement



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):

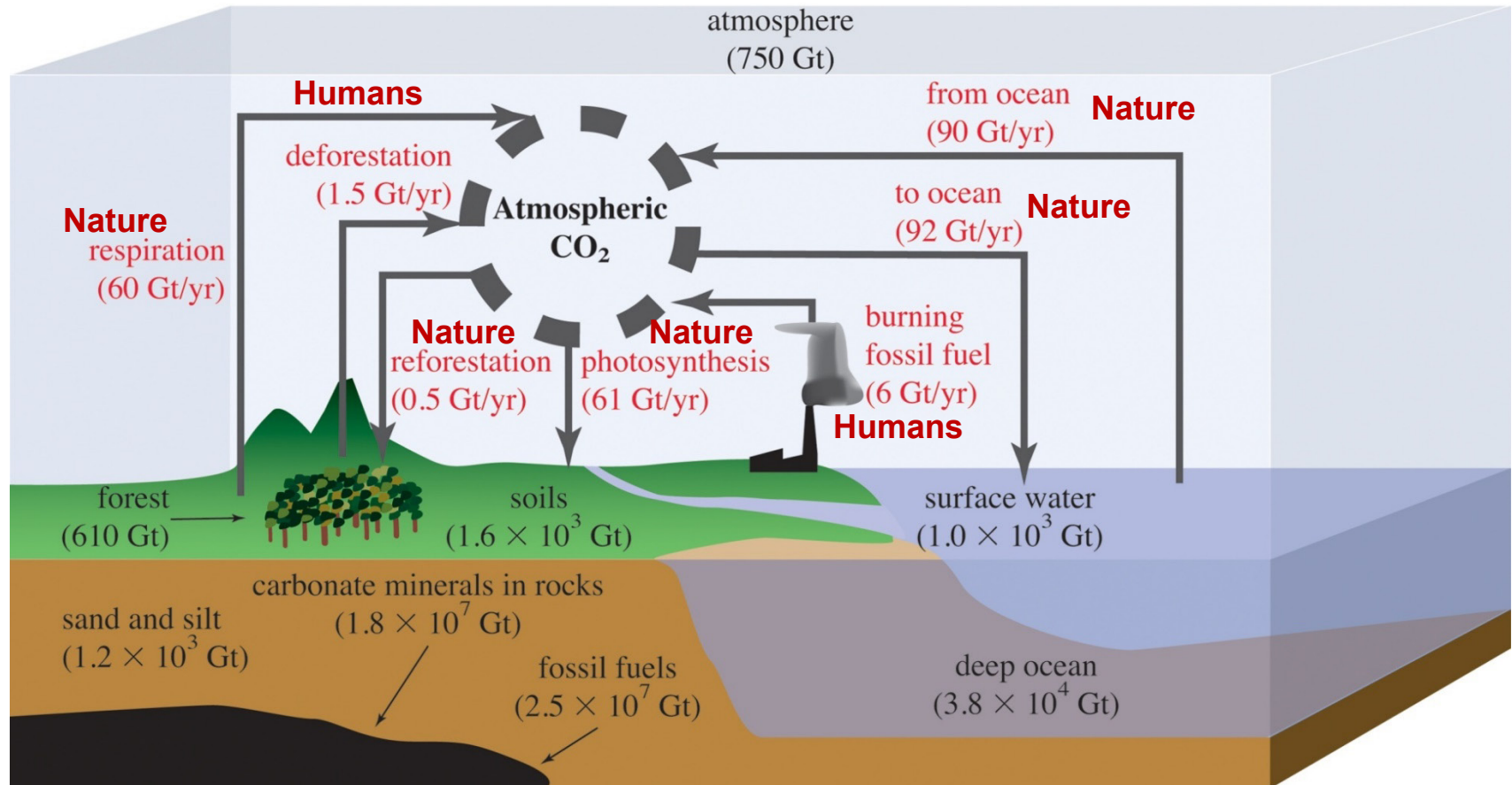
Objective to hold “increase in GMST to well below **2°C** above pre-industrial levels and to pursue efforts to limit the temperature increase to **1.5°C** above pre-industrial levels”

NDC: Nationally Determined Contributions 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

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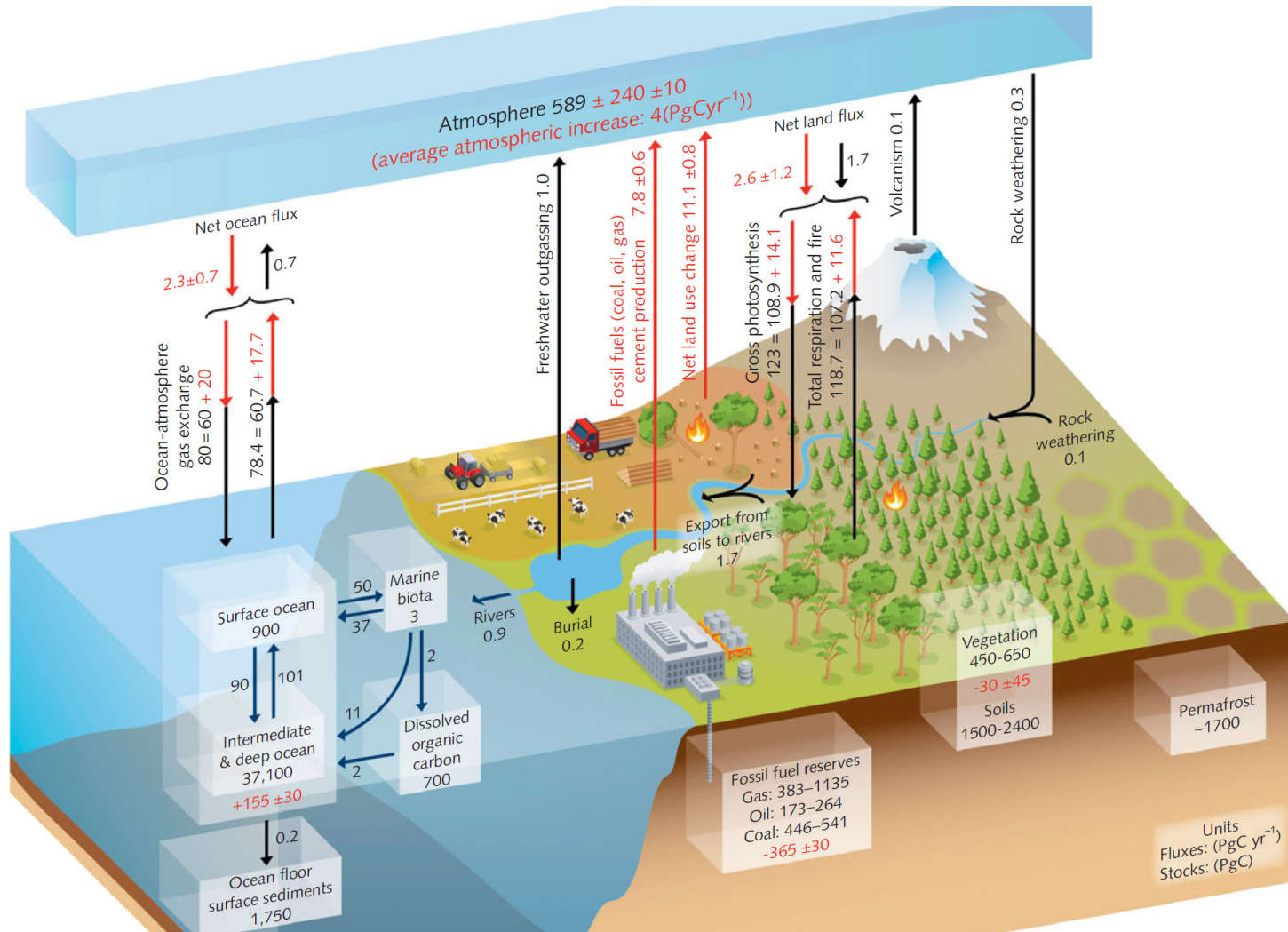
CC:

$$\text{Land Sink} = (61 + 0.5) - (60) \text{ Gt C / yr} = 1.5 \text{ Gt C / yr}$$

$$\text{Ocean Sink} = 92 - 90 \text{ Gt C / yr} = 2 \text{ Gt C / yr}$$

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 3.20, Chemistry in Context



Houghton:

Land Sink $= 2.6 \pm 1.2 \text{ Gt C / yr}$

Ocean Sink $= 2.3 \pm 0.7 \text{ Gt C / yr}$

In other words, $\sim 4.9 \text{ Gt C / yr}$ out of $7.8 + 1.1 = 8.9 \text{ Gt C / yr}$ 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 3.1, Houghton

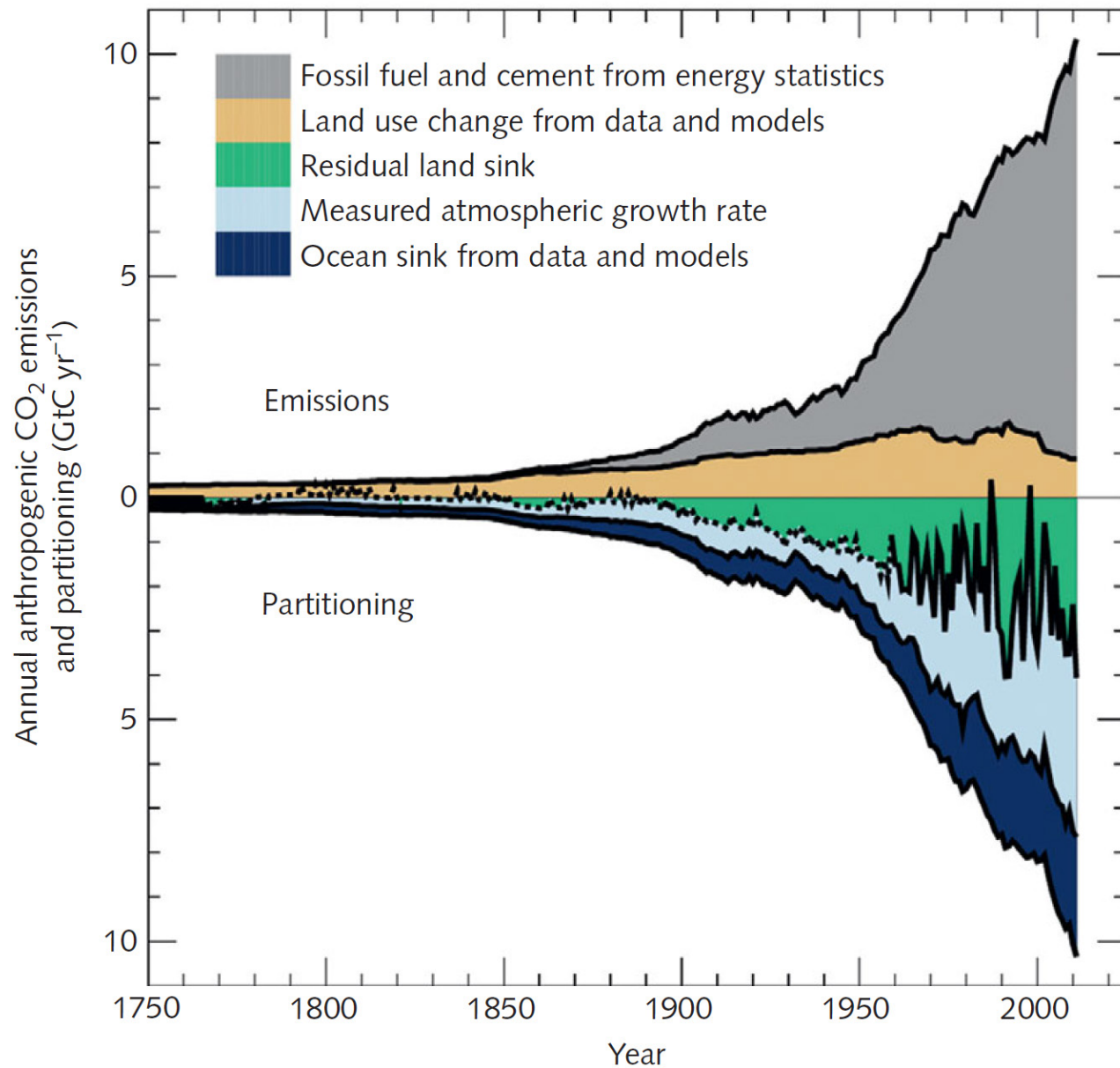
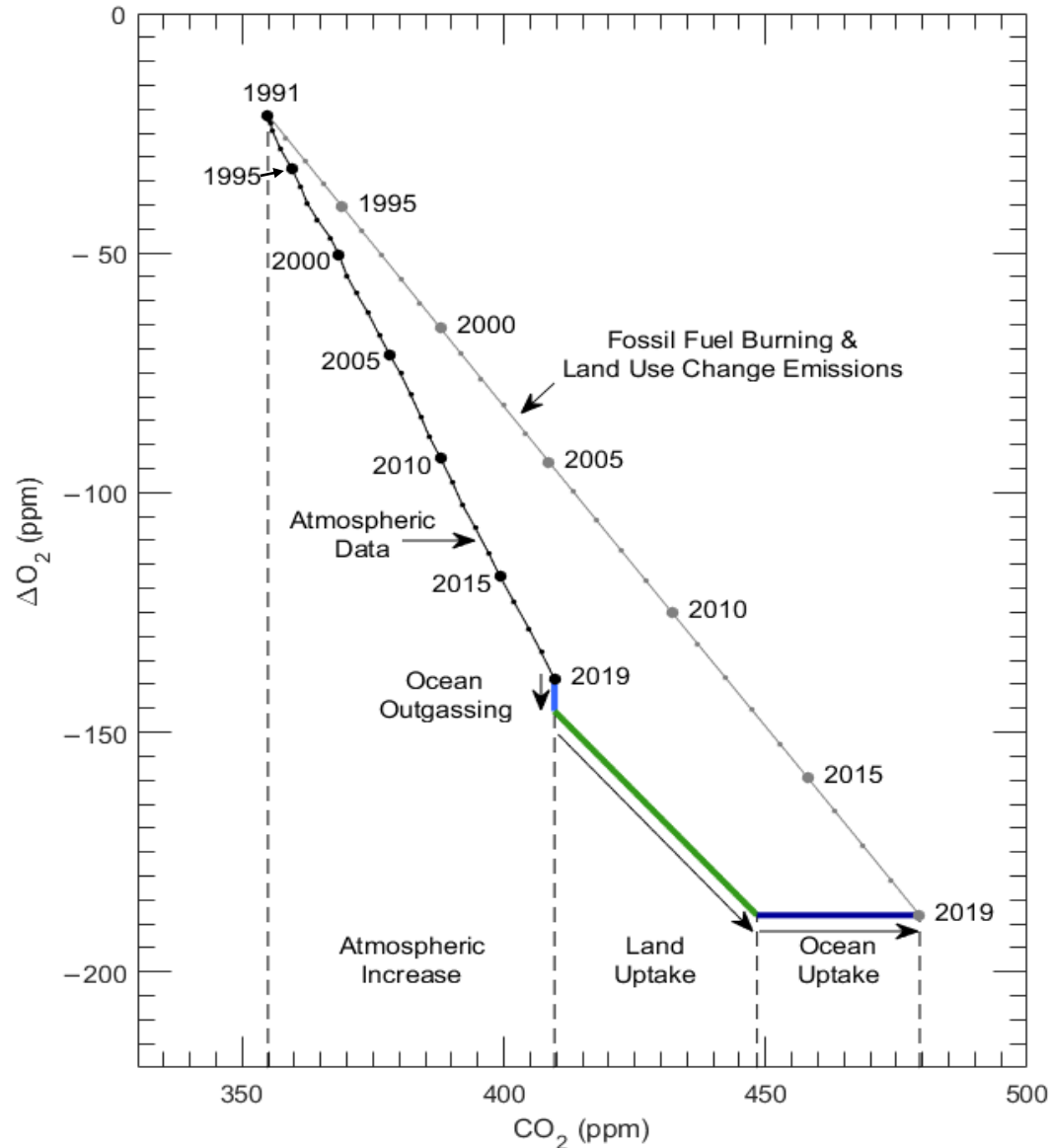


Fig 3.3, Houghton

Inferring CO₂ Uptake Based on ΔO_2

Figure courtesy
Brian Bennett



Uptake of Atmospheric CO₂ 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 CO₂ by end of century

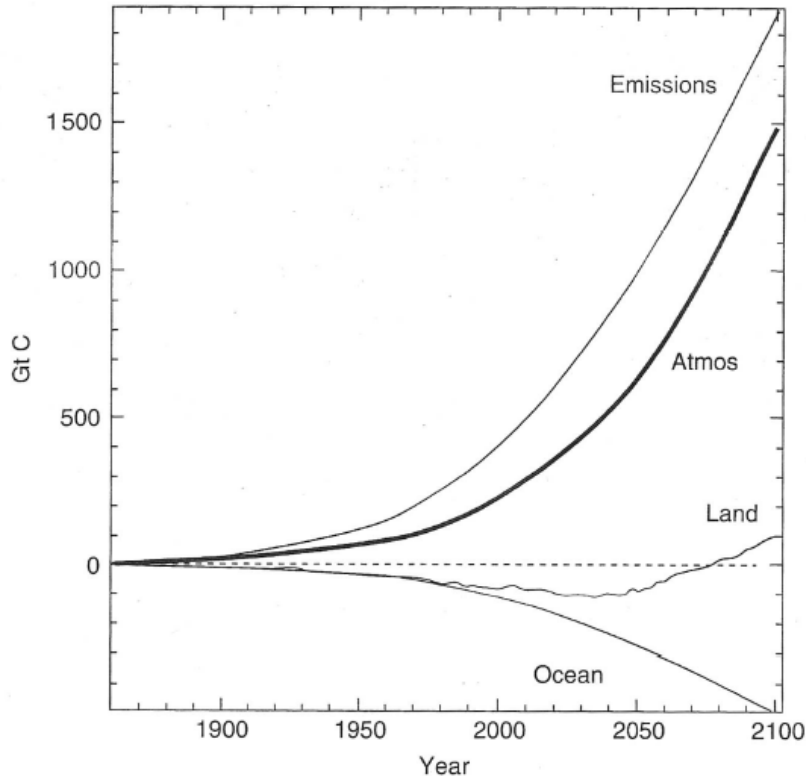
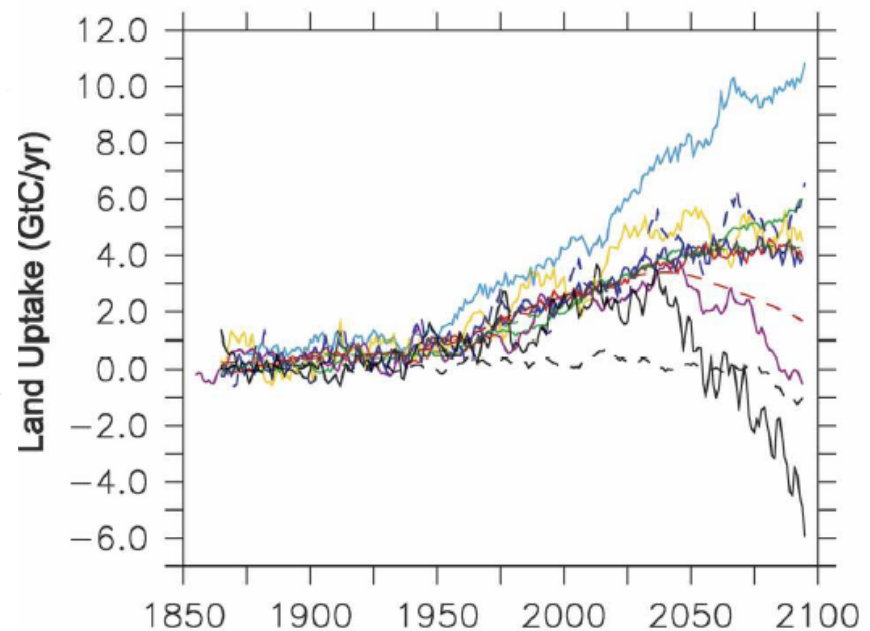


Figure 3.5 Illustrating the possible effects of climate feedbacks on the carbon cycle. Results are shown of the changing budgets of carbon

Figure 3.5, Houghton 3^d 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 CO₂ by Trees (Land Sink)

Land sink

As CO₂ ↑, photosynthesis (all things being equal) will increase.

Known as the **“CO₂ 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 CO₂ by Trees (Land Sink)

Land sink

As CO₂ ↑, photosynthesis (all things being equal) will increase.

Known as the “**CO₂ 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 CO₂ 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 CO₂

<http://aspenface.mtu.edu>

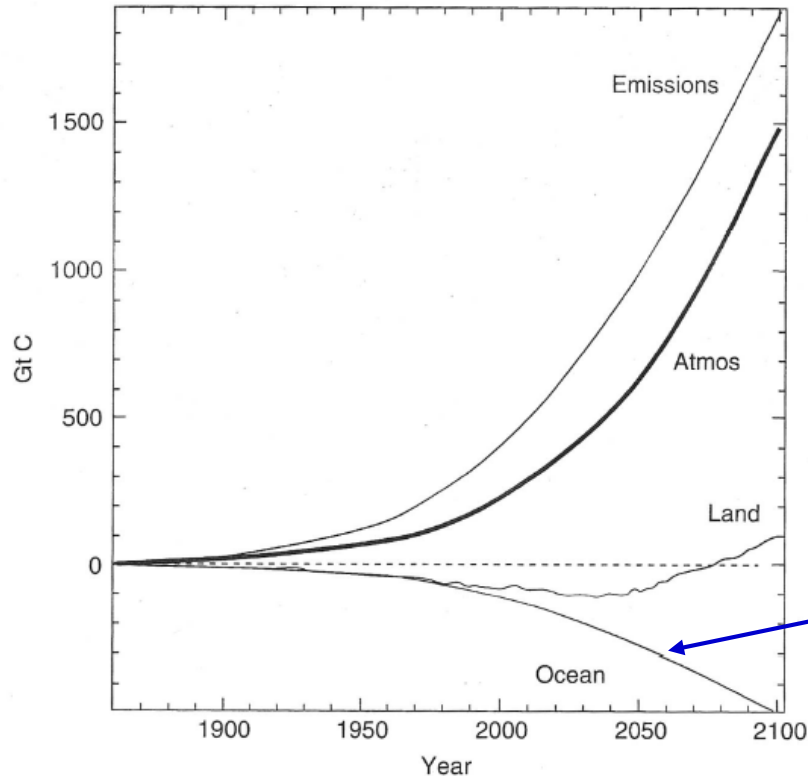
https://www.nature.com/news/polopoly_fs/1.128551/menu/main/topColumns/topLeftColumn/pdf/496405a.pdf?origin=ppub

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

Uptake of Atmospheric CO₂ 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 CO₂ by end of century



Ocean sink: relatively long lived reservoir

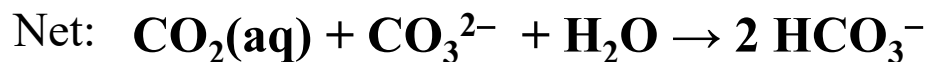
In nearly all models, ocean uptake slows relative to rise in atmospheric CO₂

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, older (Third) edition of Houghton

Uptake of Atmospheric CO₂ by Oceans

When CO₂ dissolves:



Atmospheric CO ₂	280 ppm Pre-Industrial	411 ppm Present Day	560 ppm 2 × Pre-Indus.
Ocean Carbon	$2020 \times 10^{-6} \text{ M}$	$2079 \times 10^{-6} \text{ M}$	$2122 \times 10^{-6} \text{ M}$
[HCO ₃ ⁻]	$1771 \times 10^{-6} \text{ M}$	$1882 \times 10^{-6} \text{ M}$	$1958 \times 10^{-6} \text{ M}$
[CO ₂ (aq)]	$9.13 \times 10^{-6} \text{ M}$	$13.4 \times 10^{-6} \text{ M}$	$18.3 \times 10^{-6} \text{ M}$
[CO ₃ ²⁻]	$239 \times 10^{-6} \text{ M}$	$148 \times 10^{-6} \text{ M}$	$146 \times 10^{-6} \text{ M}$
pH	8.32	8.18	8.06

Ocean Carbon $[\Sigma \text{CO}_2] = [\text{CO}_2(\text{aq})] + [\text{HCO}_3^-] + [\text{CO}_3^{2-}]$

Notes:

T = 293 K; Alkalinity = $2.25 \times 10^{-3} \text{ M}$

M ≡ mol/liter

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

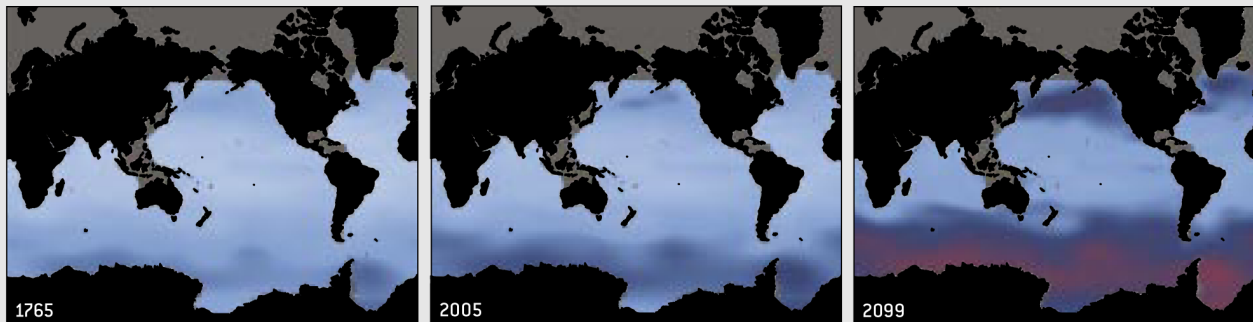
Uptake of Atmospheric CO₂ by Oceans

Oceanic uptake of atmospheric CO₂ leads to **ocean acidification**

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

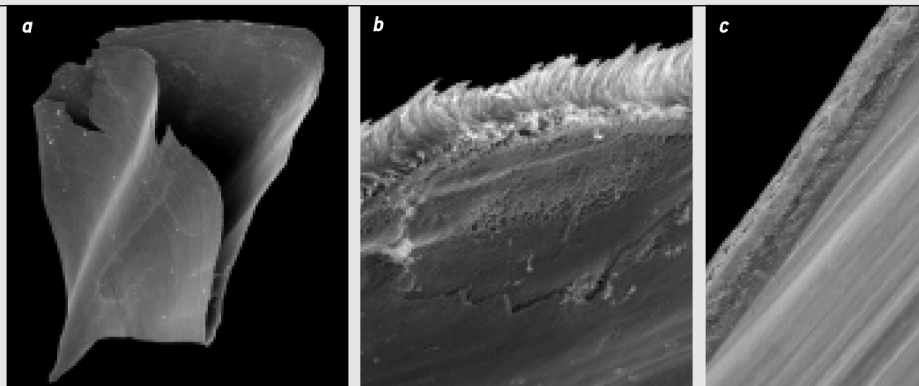
THE (RAGGED) FUTURE OF ARAGONITE

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.

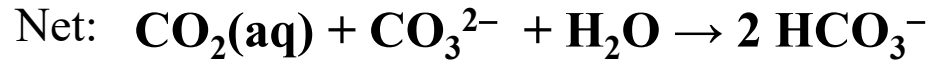
Pteropods form a key link in the food chain throughout the Southern Ocean. For these animals (and creatures that depend on them), the coming changes may be disastrous, as the images at the right suggest. The shell of a pteropod kept for 48 hours in water undersaturated with respect to aragonite shows 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

Uptake of Atmospheric CO₂ by Oceans

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Revelle Factor:

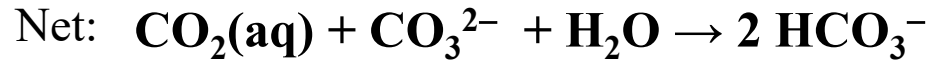
$$\frac{\Delta \text{Atmos}_{\text{CO}_2}}{\langle \text{Atmos}_{\text{CO}_2} \rangle_{\text{AVERAGE}}} = \frac{131 \text{ ppm}}{0.5 \times (411 + 280) \text{ ppm}} = 0.34$$

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

Pre-industrial to present: Ocean carbon rose by 2.9% for a 34% increase in atmospheric CO₂

Uptake of Atmospheric CO₂ by Oceans

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pH	8.32	8.18	8.06

Revelle Factor:

$$\frac{\Delta \text{Atmos}_{\text{CO}_2}}{\langle \text{Atmos}_{\text{CO}_2} \rangle_{\text{AVERAGE}}} = \frac{149 \text{ ppm}}{0.5 \times (560 + 411) \text{ ppm}} = \mathbf{0.31}$$

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

Present to a future we hope to avoid: Ocean carbon will rise by 2.0% for a 31% increase in atmospheric CO₂