

Past perfect, future imperfect?

Carbon cycle biases in reduced complexity climate models

Dargan Frierson, UW ATMOS, Laura Bassi Fellow, CMCC
ICTP, 27-01-26

Research inspired by teaching...

- My teaching assignment in early 2020: design a new climate solutions course
 - I decided to teach **Climate, Justice and Energy Solutions: 100% Clean Energy for 100% of the People**
 - What is climate justice? Who decides?
 - Can we model it?

Free book, available online!

Climate, Justice and Energy Solutions

Radical Visions of 100% Clean Power for 100% of the People

Dargan M. W. Frierson



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READ BOOK



Environmental Justice Documents

- Principles of Environmental Justice (1991)
- UN Declaration of Rights of Indigenous Peoples (2007)
- Universal Declaration for the Rights of Mother Earth (2010)
- And many more...



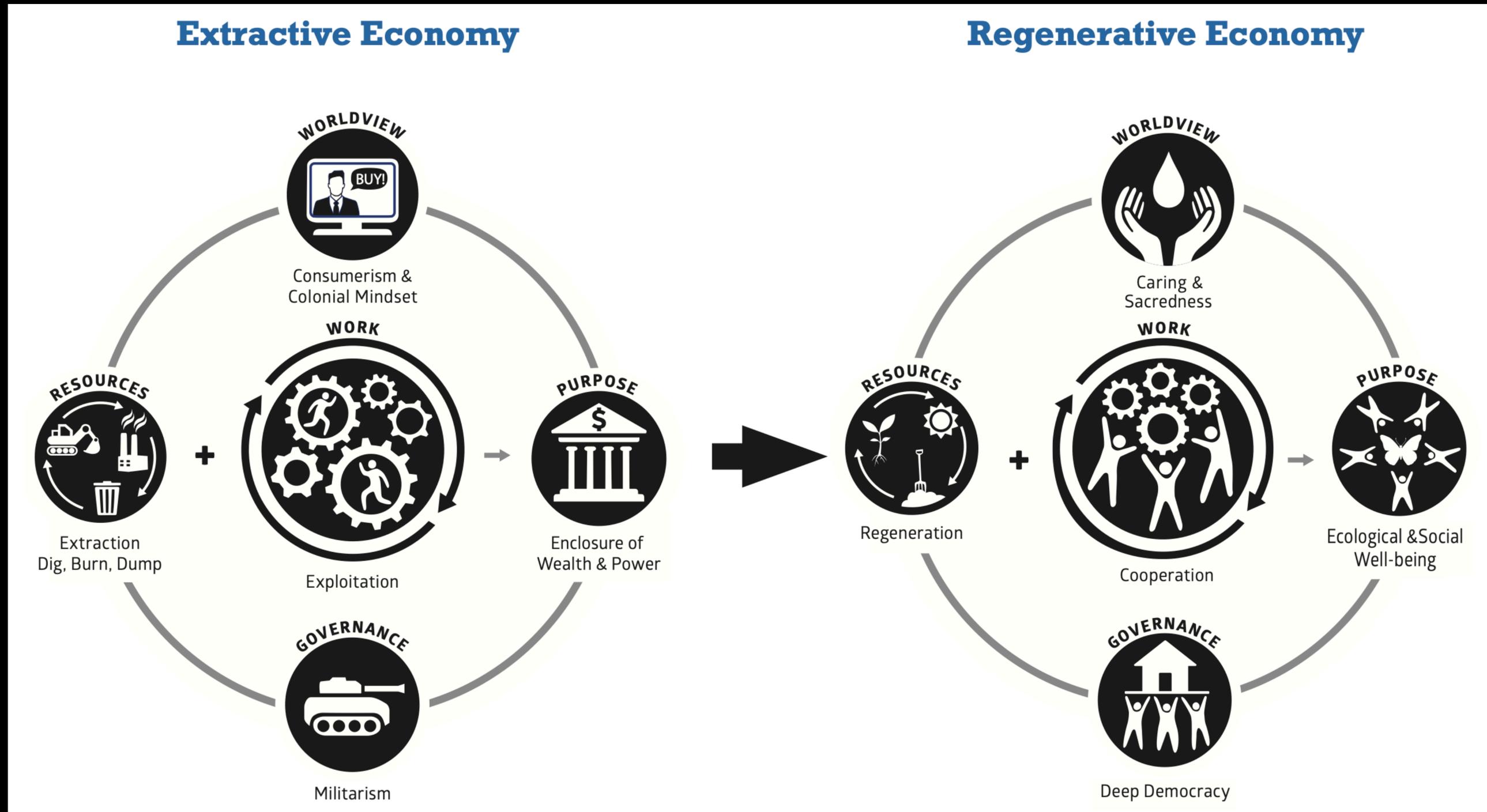
Environmental Justice Stories

- EJ Atlas (ejatlas.org) is an archive of thousands of environmental justice struggles from around the world
 - Including many successes, where protests were successful
- In Trieste: Ferriera di Servola, which was a large source of particulate matter pollution & carcinogens
 - Greatly elevated risk for cancer among workers, hundreds sickened
 - Closed in 2020



Climate Action?

- Systems thinking solutions rather than reductionist solutions



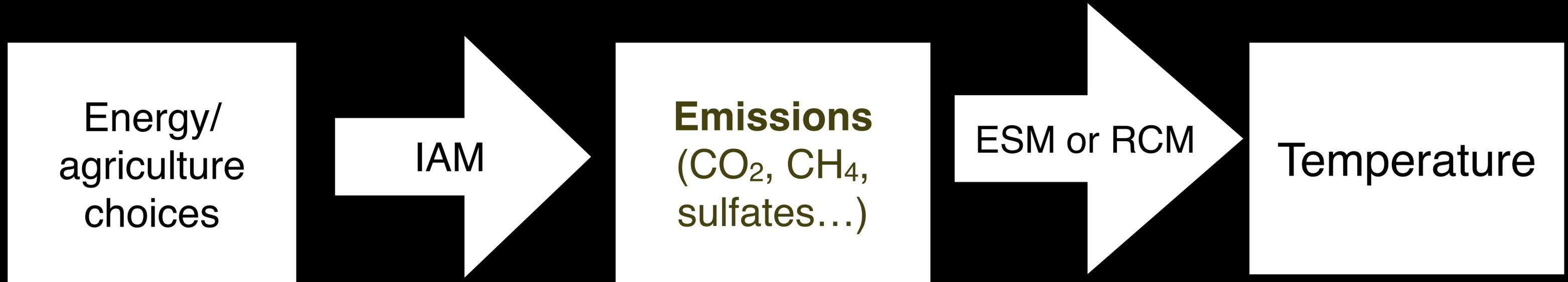
Can we model futures like this?

- Can we increase **access** to climate and energy modeling tools?
- Can we help others envision their own climate futures?

- To start, how are scenarios and temperature forecasts constructed for the IPCC Reports?

The IPCC process for modeling

- To answer, e.g., which scenarios stay under 1.5 C or 2 C?

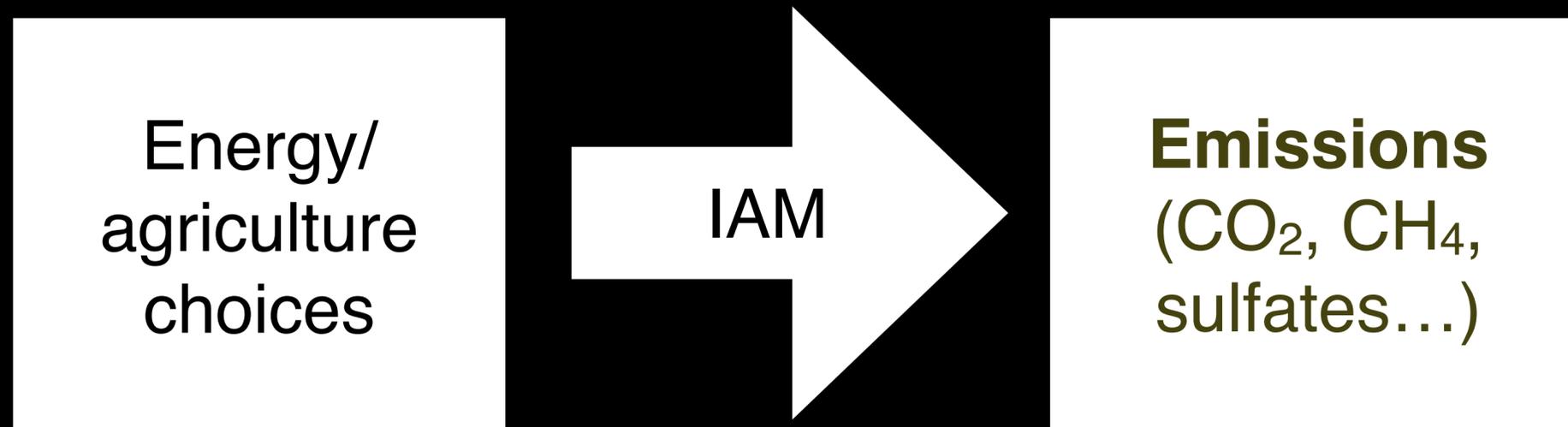


IAM = Integrated Assessment Model (economic model)

ESM = Earth System Model
RCM = Reduced Complexity Model

The IPCC process for modeling

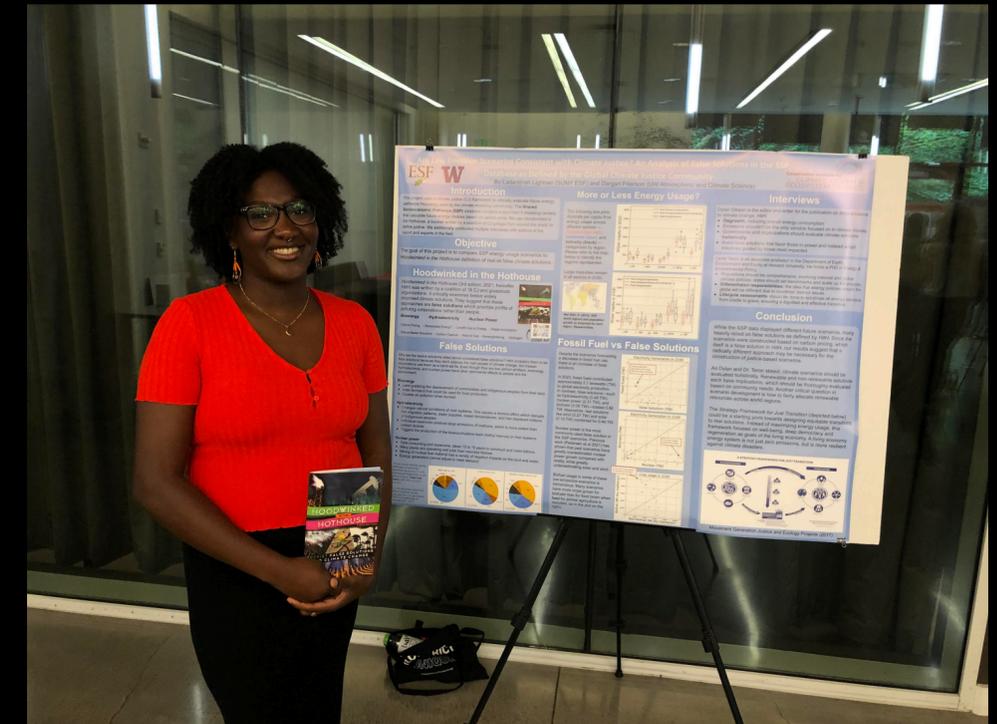
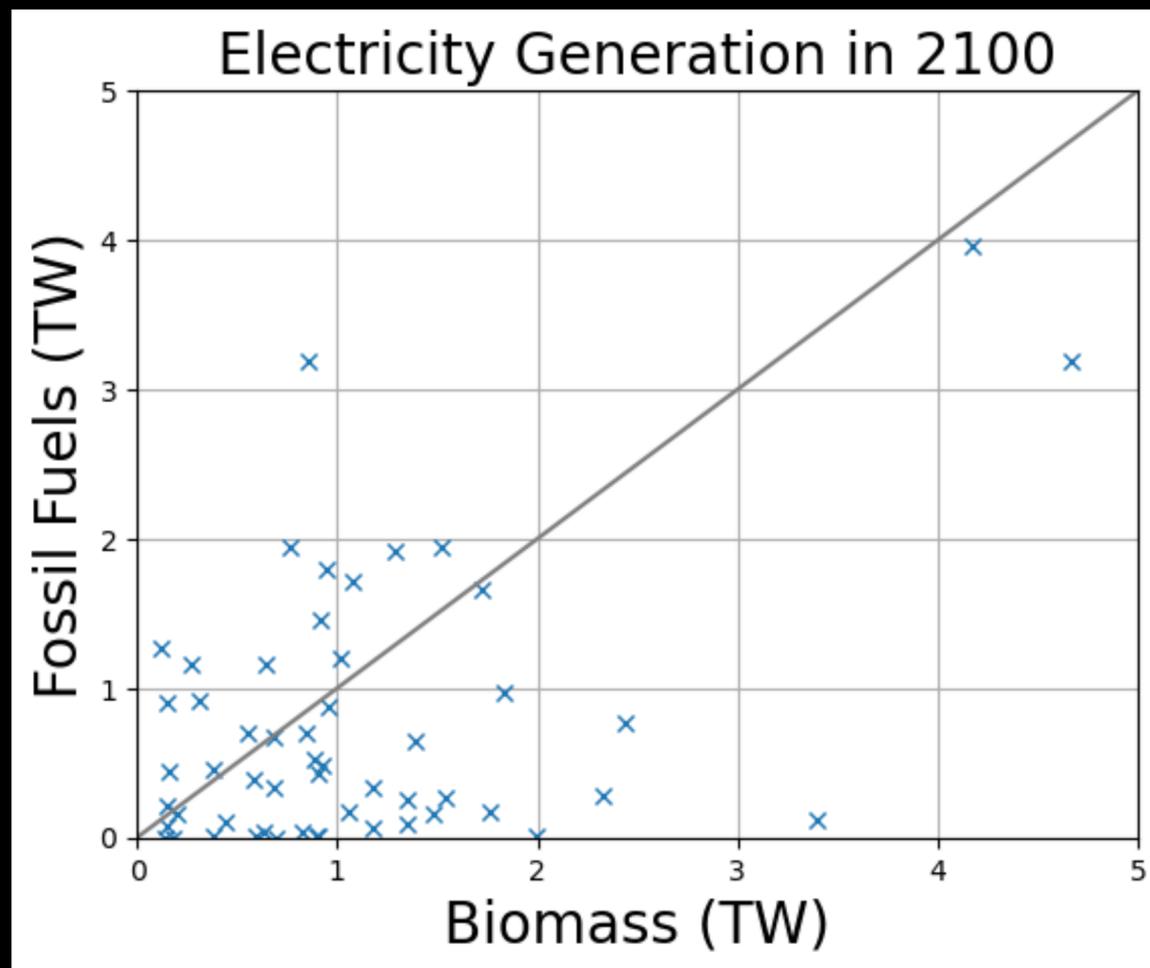
- First, emissions scenarios!



IAM = Integrated Assessment Model (economic model)

A critical analysis of IPCC scenarios

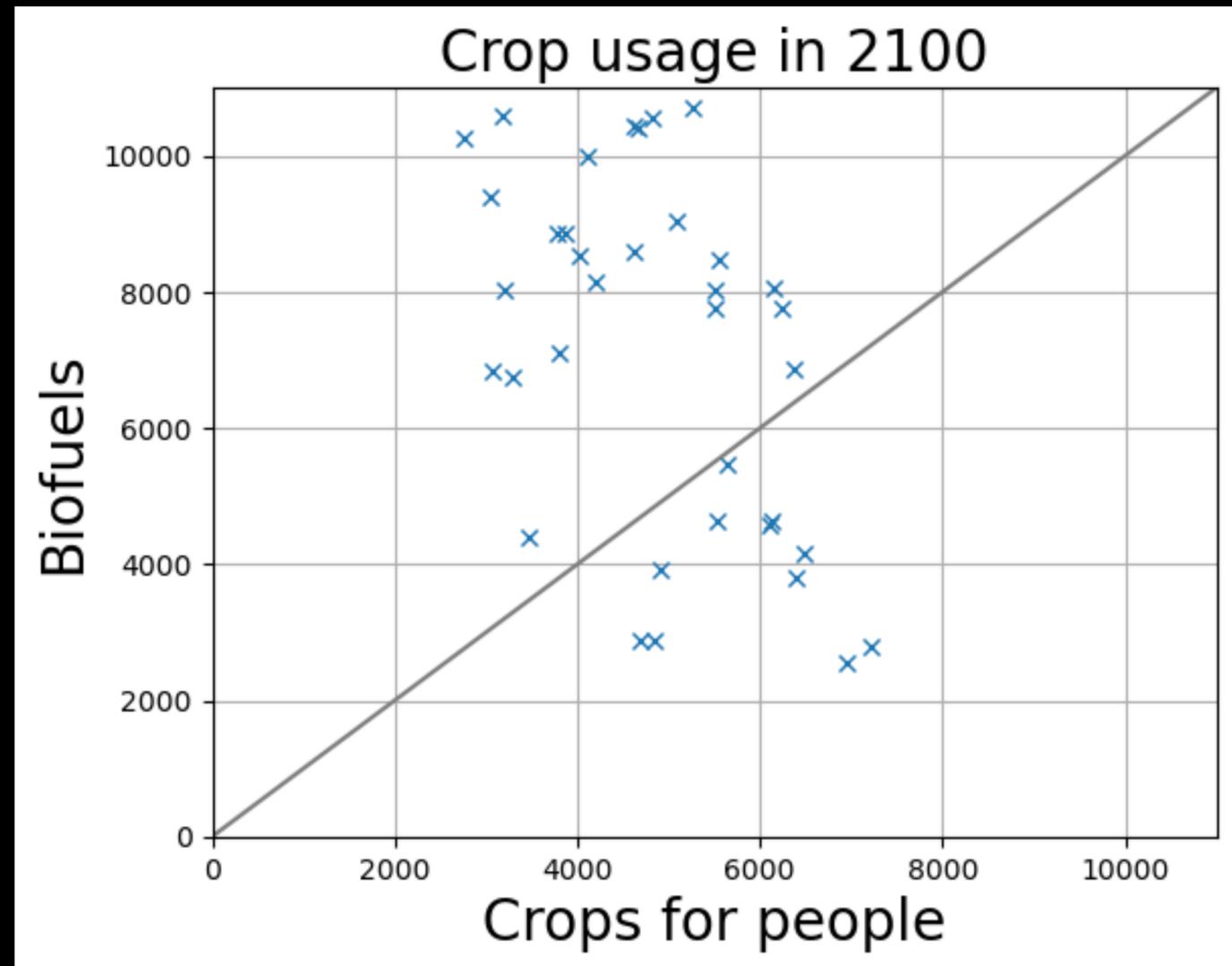
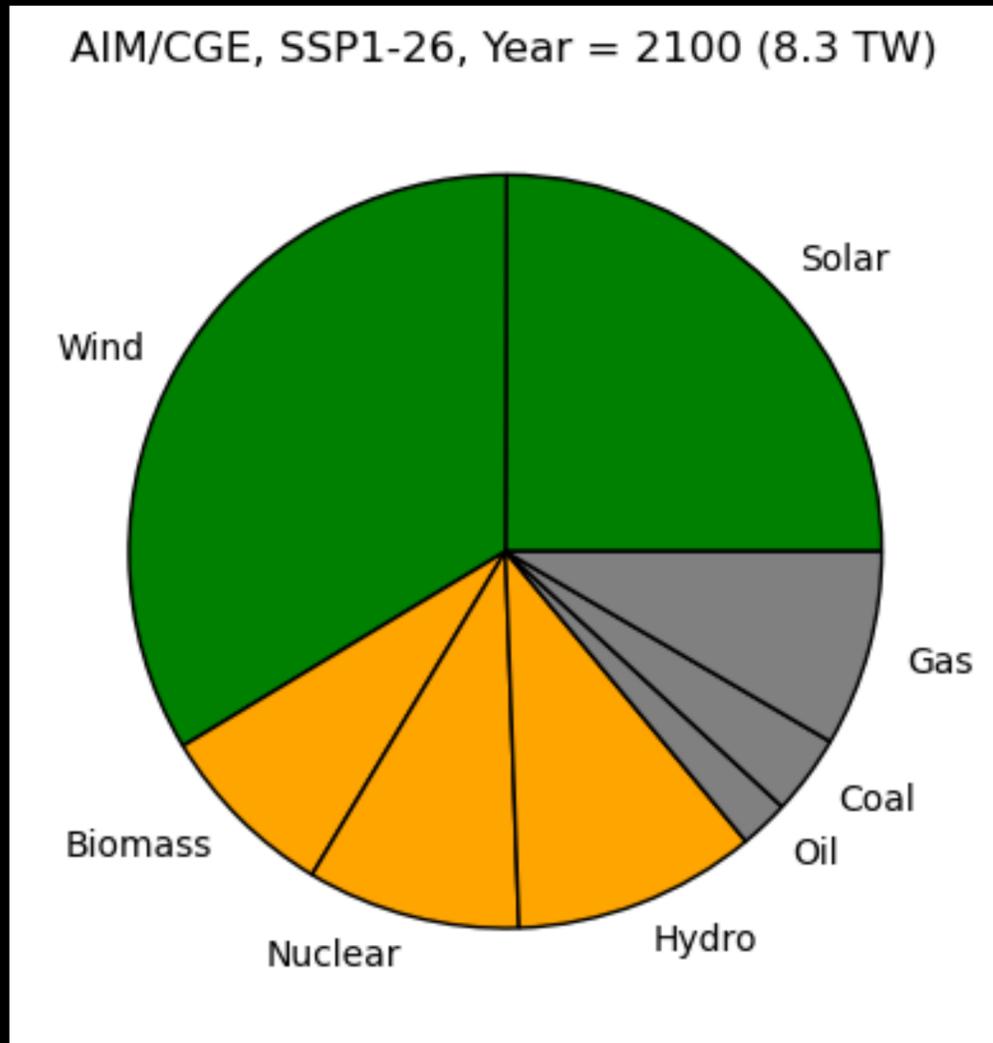
- LJ analyzed electricity generation in low emissions SSP scenarios
- Many scenarios still use fossil fuels in 2100!



Undergrad researcher
Ladanijarah Lightner

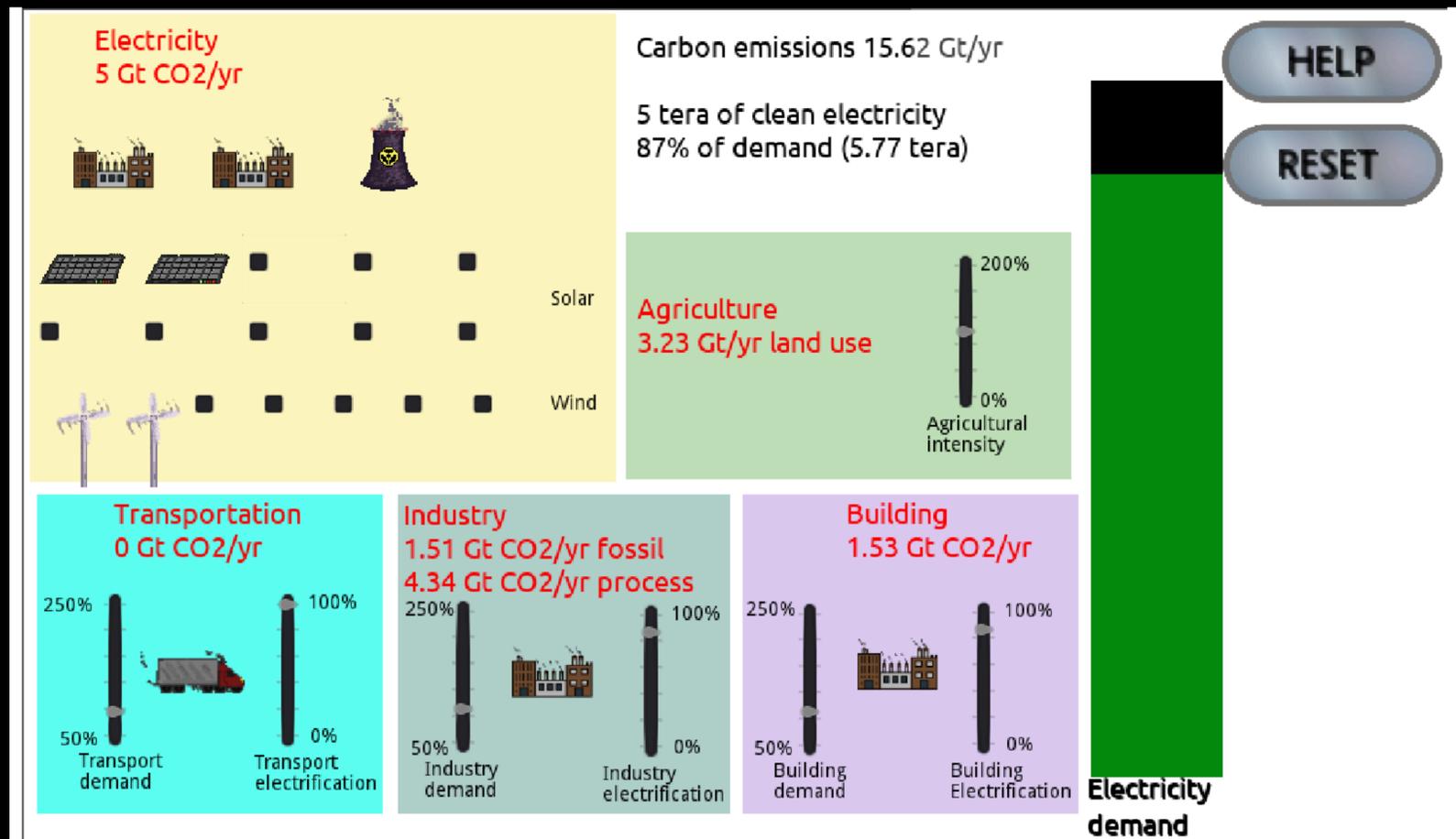
IPCC Scenarios

- **Bioenergy** with carbon capture and storage is huge in almost all these scenarios (up to 3x as much as food for people!)



Create Your Own Scenarios

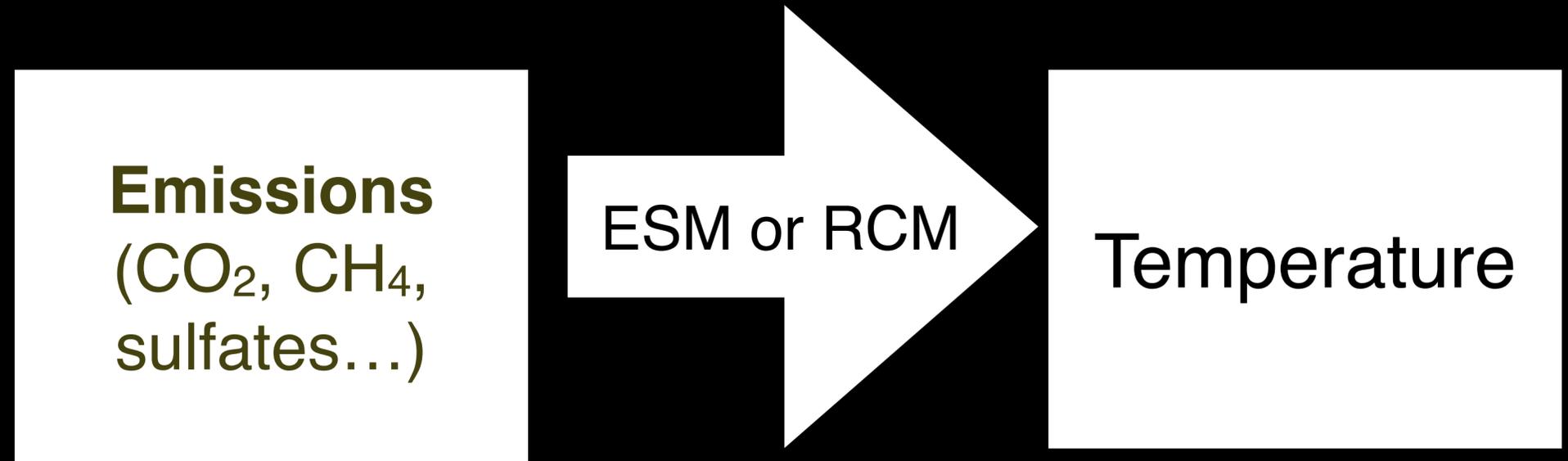
- Generate clean electricity and electrify everything



- **Post-growth** community is modeling scenarios that have elements of the regenerative economy

The IPCC process for modeling

- Now let's consider the **emissions to temperature** step...



ESM = Earth System Model

RCM = Reduced Complexity Model

World without Industry

- Let's get some intuition for **emissions to temperature** calculations
- Consider, as a simple example, what happens if all emissions are turned off immediately
 - Of fossil fuels, methane, air pollution, everything...

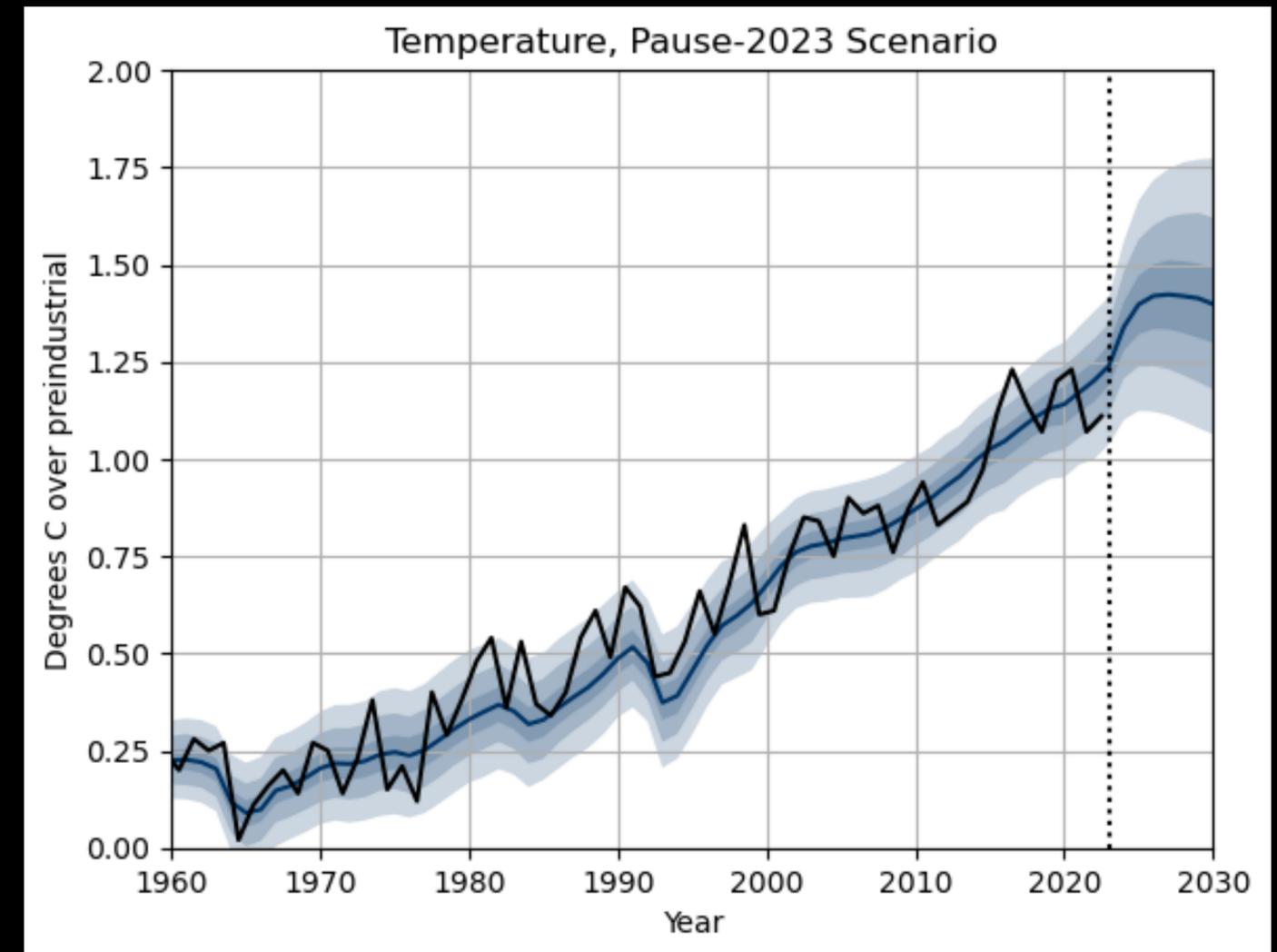
Days: Air Pollution Disappears

- Air pollution decreases within a week or so
- Immediate health benefits



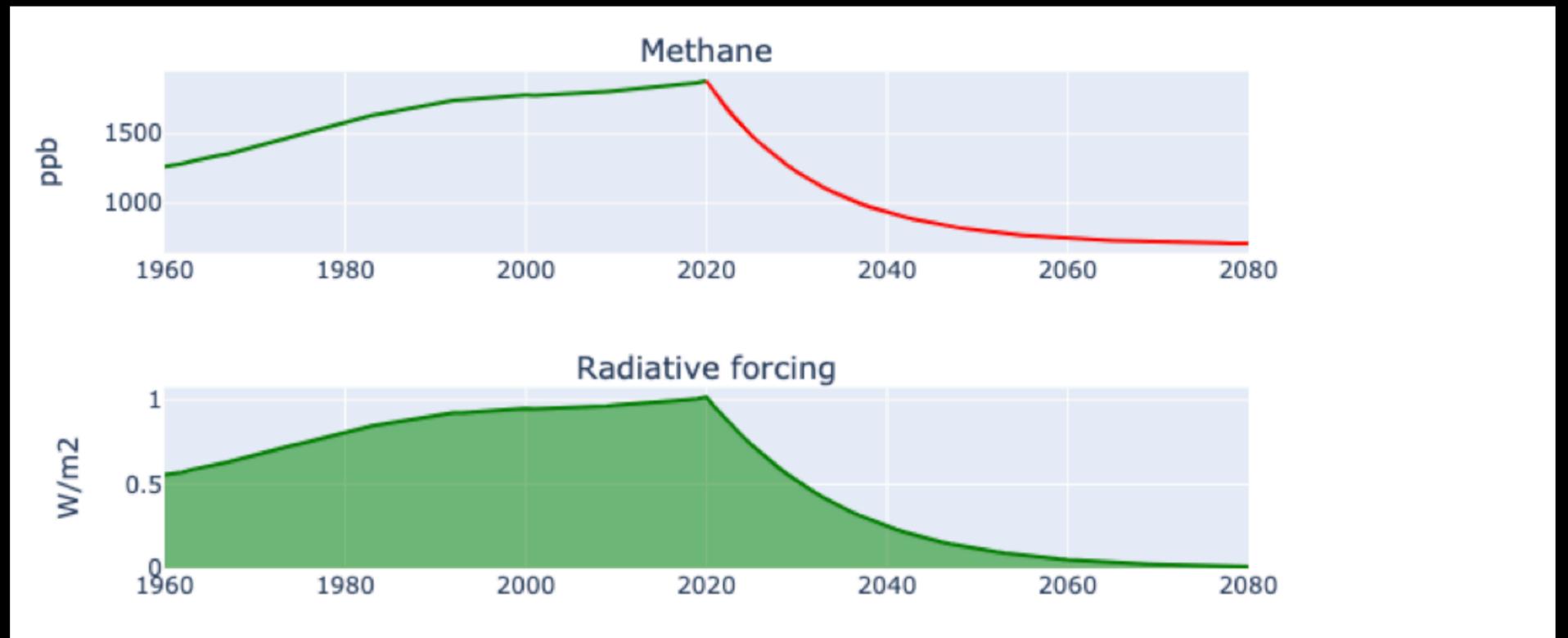
Months: More Sunlight Absorbed

- Aerosols can absorb or reflect sunlight
- Reflection is currently large (and quite uncertain)
- Temperatures rise sharply in first few years following shutdown



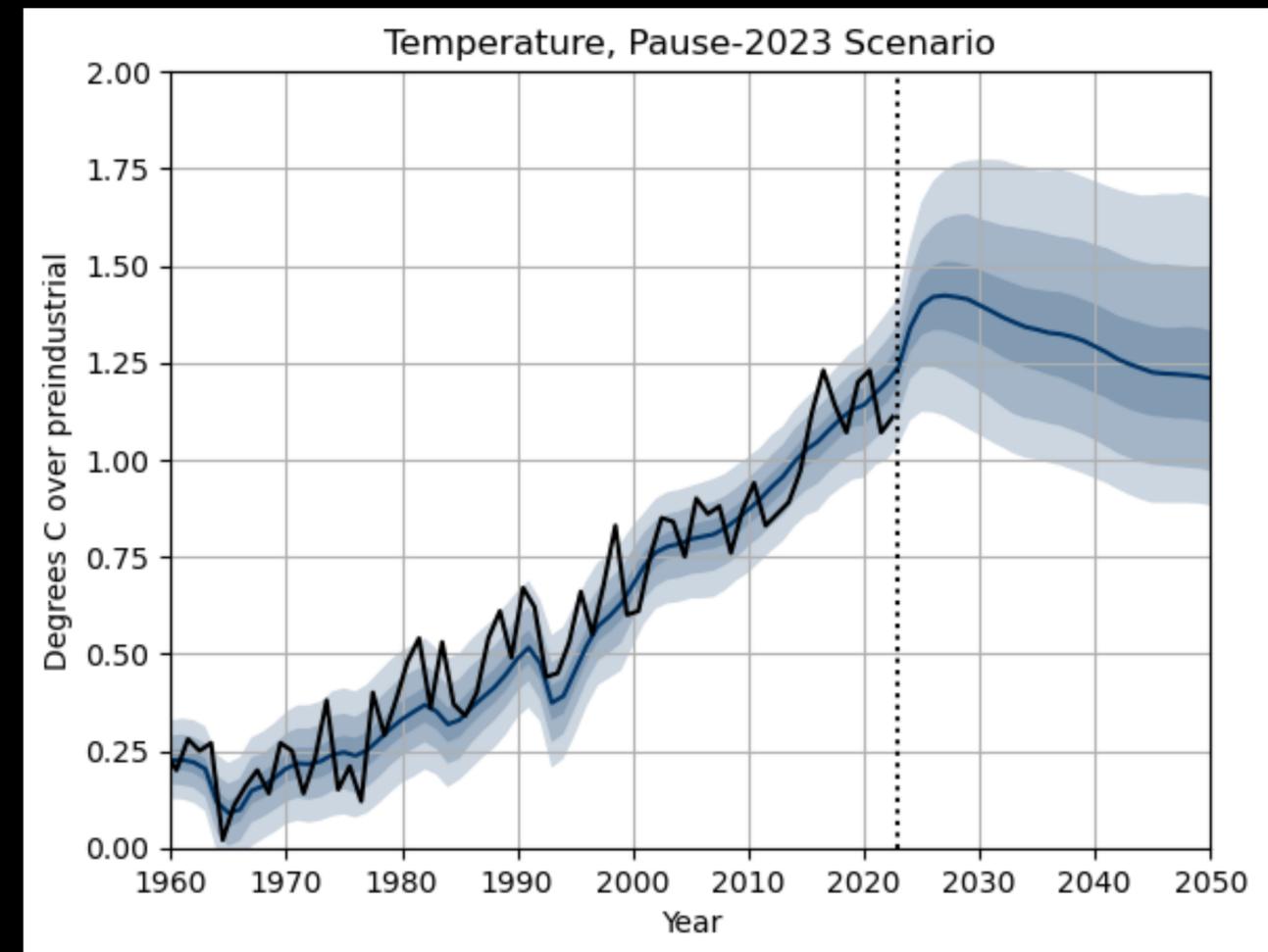
Years: Methane Decreases

- Methane (CH_4) is a stronger heat-trapping gas with lifetime of around a decade
- Within ten years, its concentrations are lower than in 1960



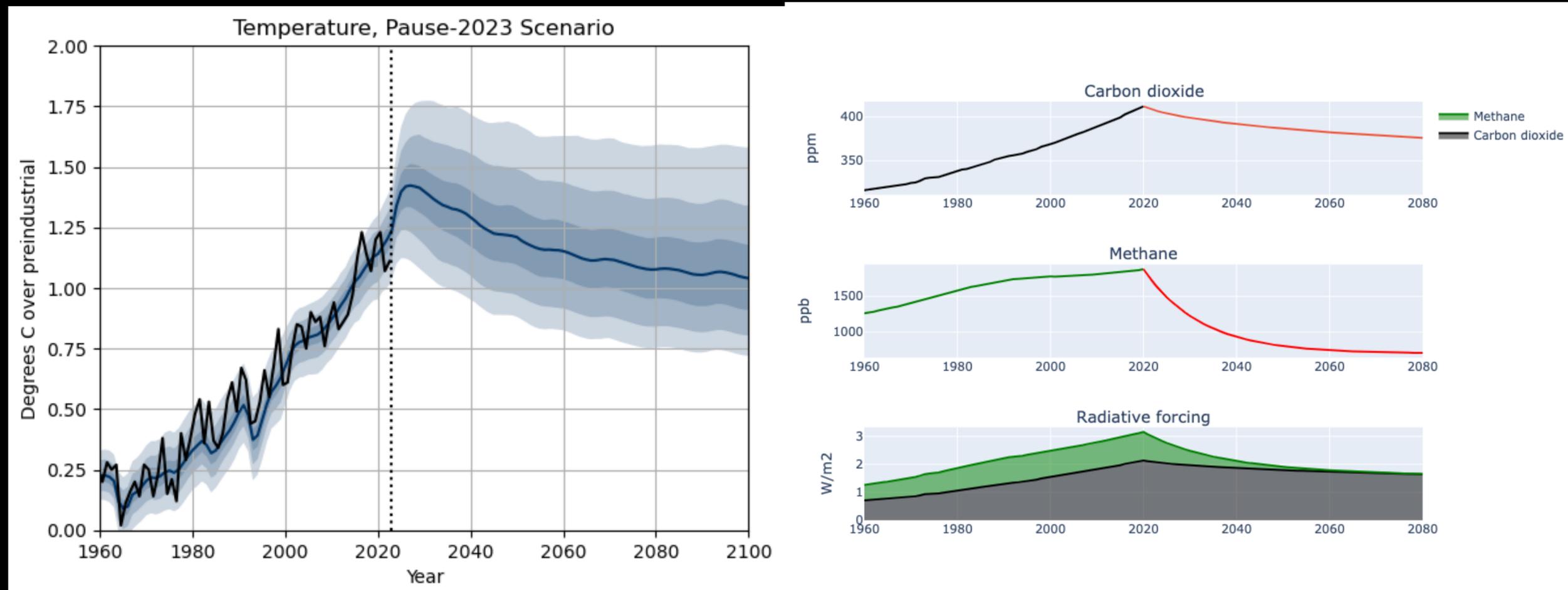
Decades: Temperature Decreases

- Temperature stays above current levels until 2050ish
- Sea ice follows global temperature (reversibly)
- So does hydrologic cycle and its extremes
- More extreme rain and droughts when it's hotter



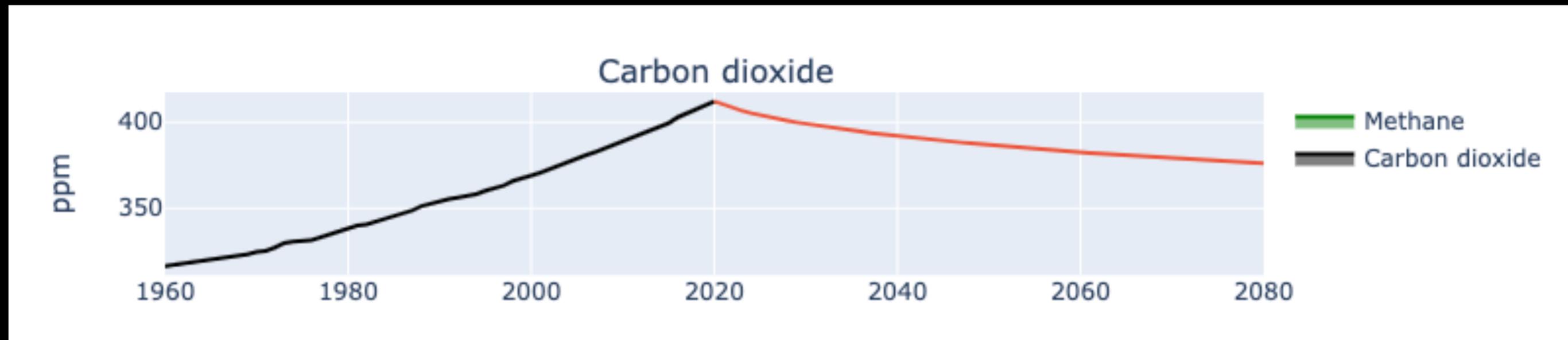
Throughout the Century: Stays Warm

- Carbon dioxide is still high in concentration
- Only drops to 2009 levels by 2050
- Temperatures stay warm too



The Carbon Cycle

- Carbon dioxide has **fast uptake into surface ocean (years)**
- **Land removal over decades**
- **Deep ocean removal takes centuries**
- **Extremely slow removal via chemical weathering (100,000 years)**



Given emissions, how to get CO₂?

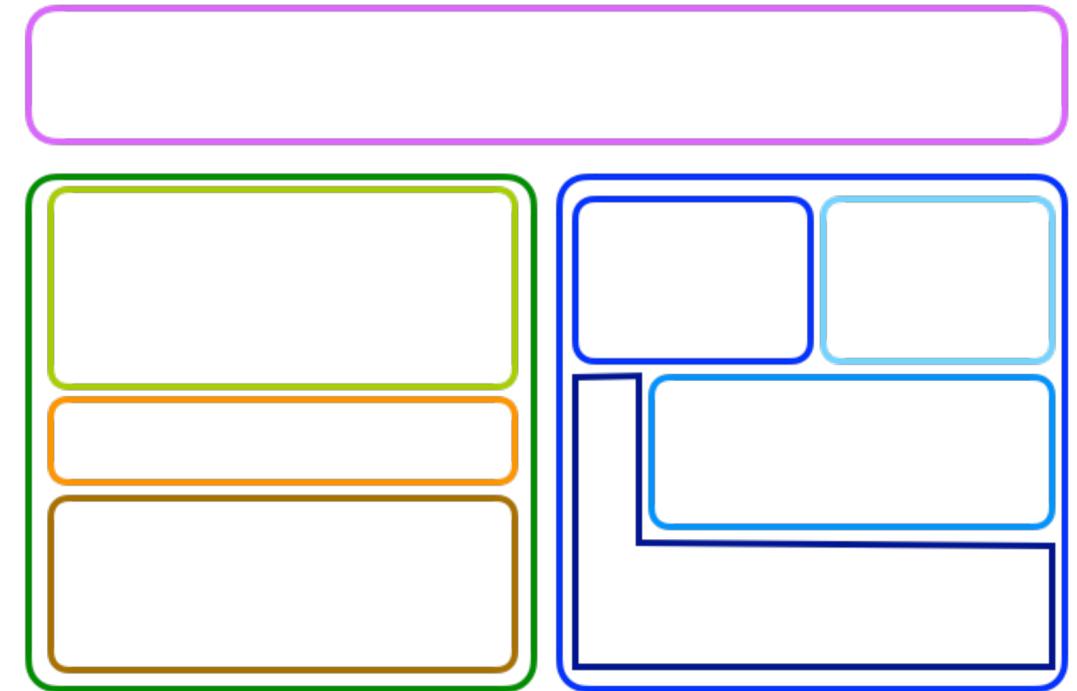
- Earth System Models (ESMs) simulate the carbon cycle, but are **not** usually used to run scenarios
 - All SSP scenarios were run with **fixed concentrations** (except esm-ssp585, with very high emissions)
- Instead **reduced complexity models** are used...
 - Examples: fair, MAGICC, hector

The carbon cycle of reduced complexity climate models

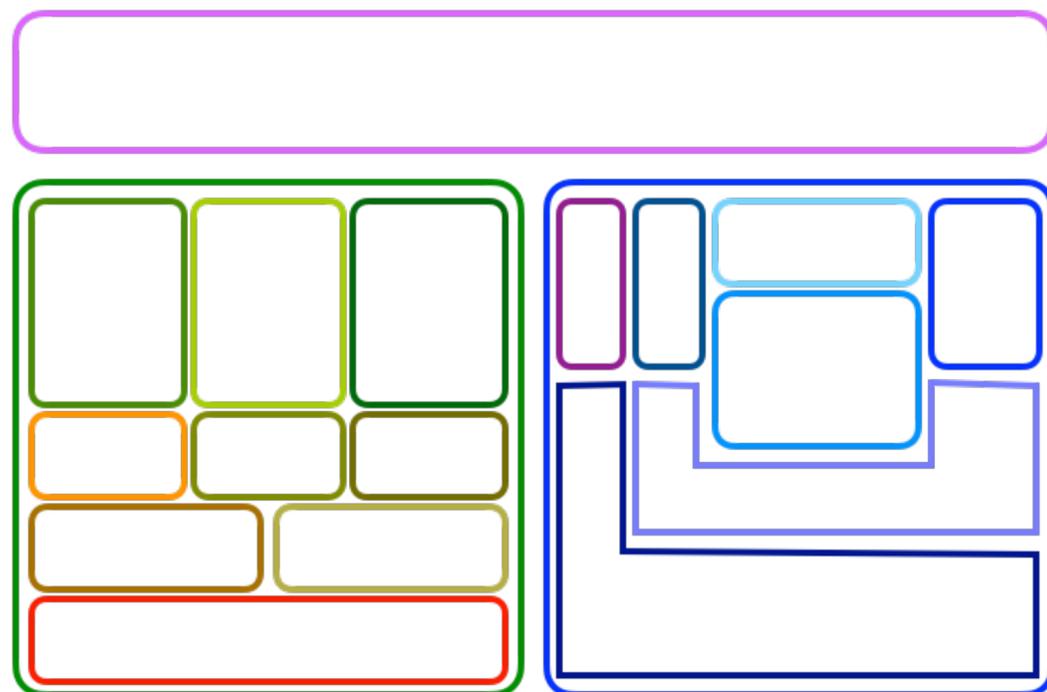
AR5-IR and FaIR



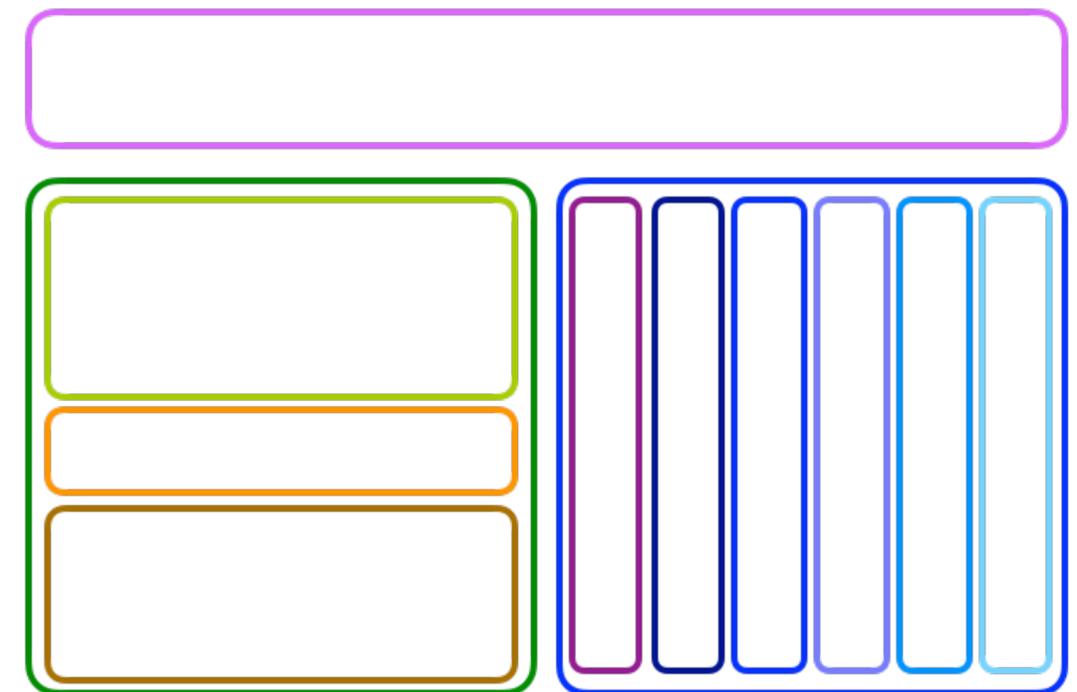
HECTOR



Swann/Deutsch



MAGICC

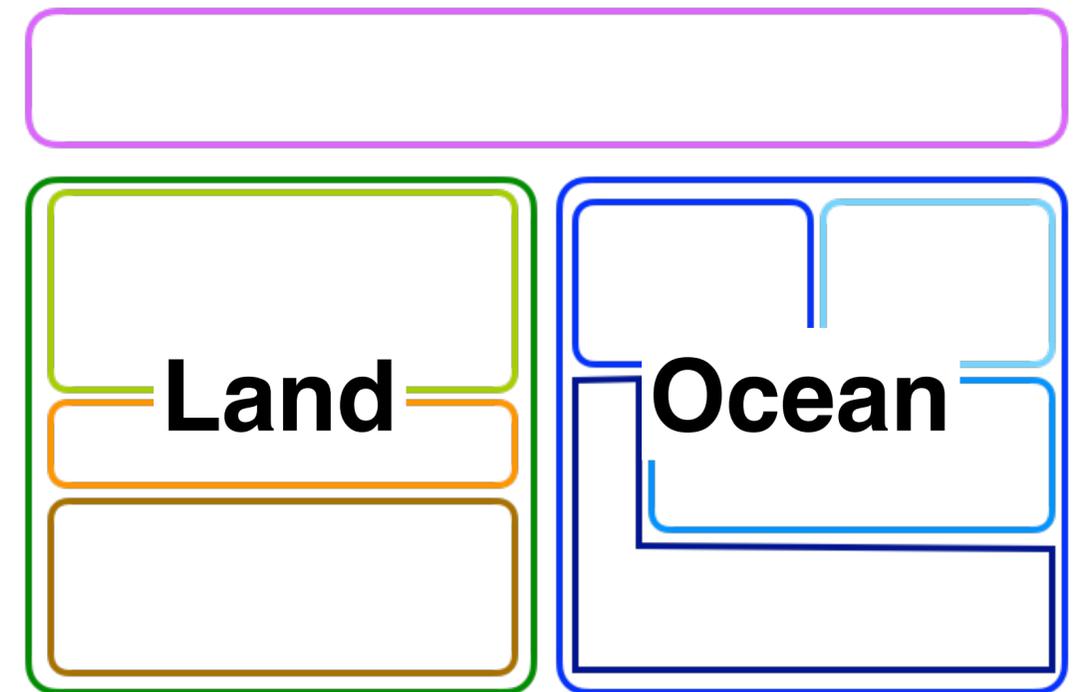


The carbon cycle of reduced complexity climate models

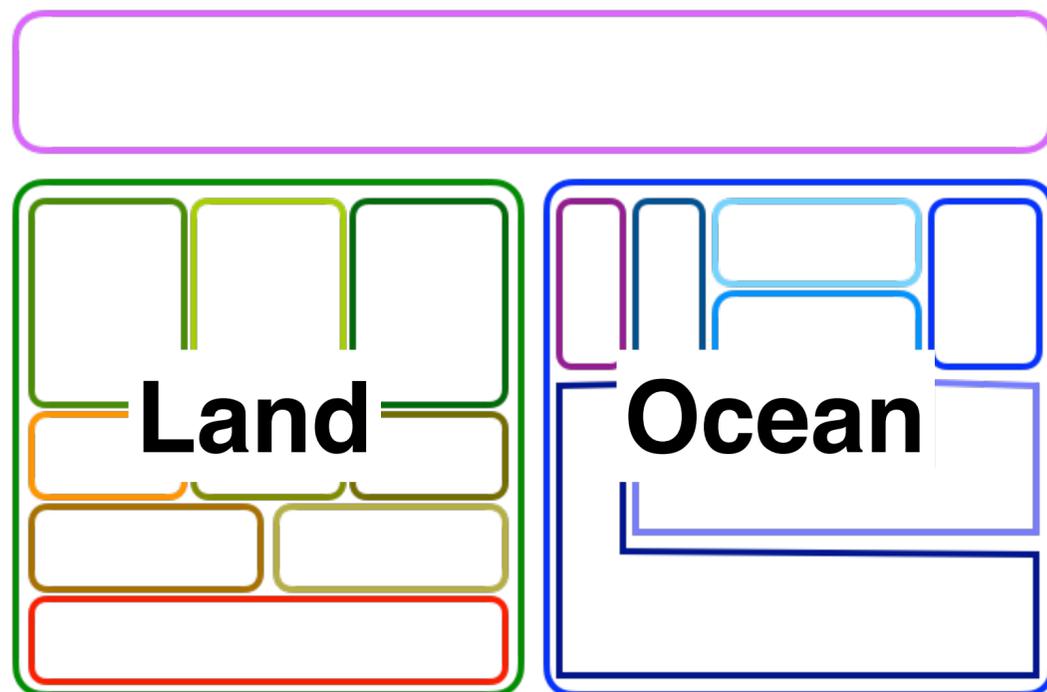
AR5-IR and FaIR



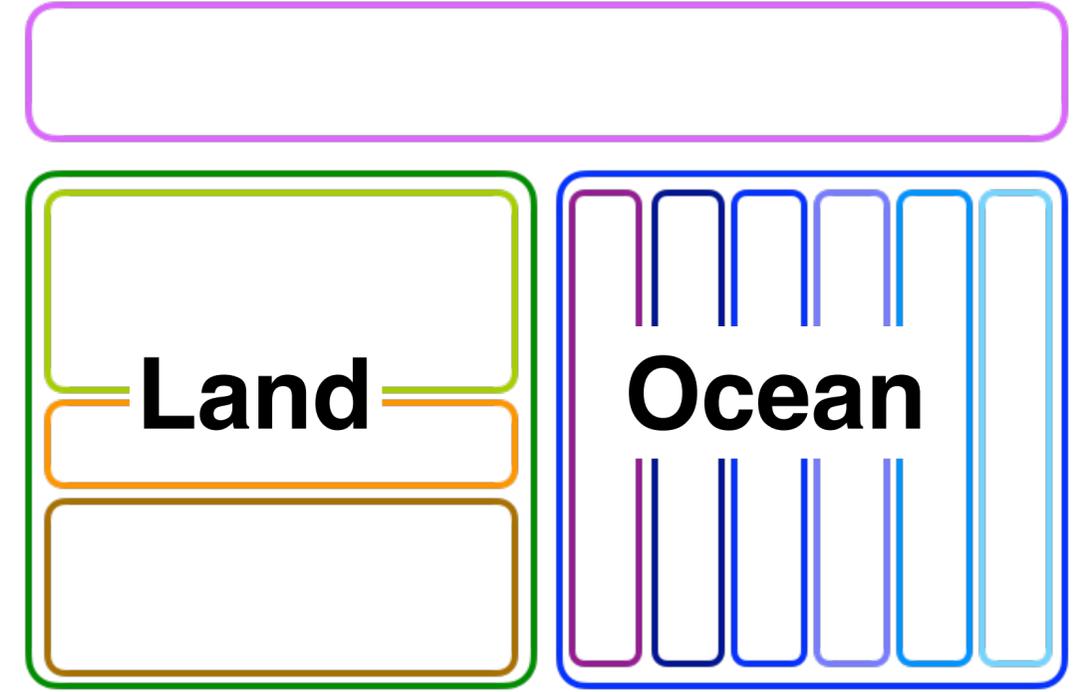
HECTOR



Swann/Deutsch



MAGICC

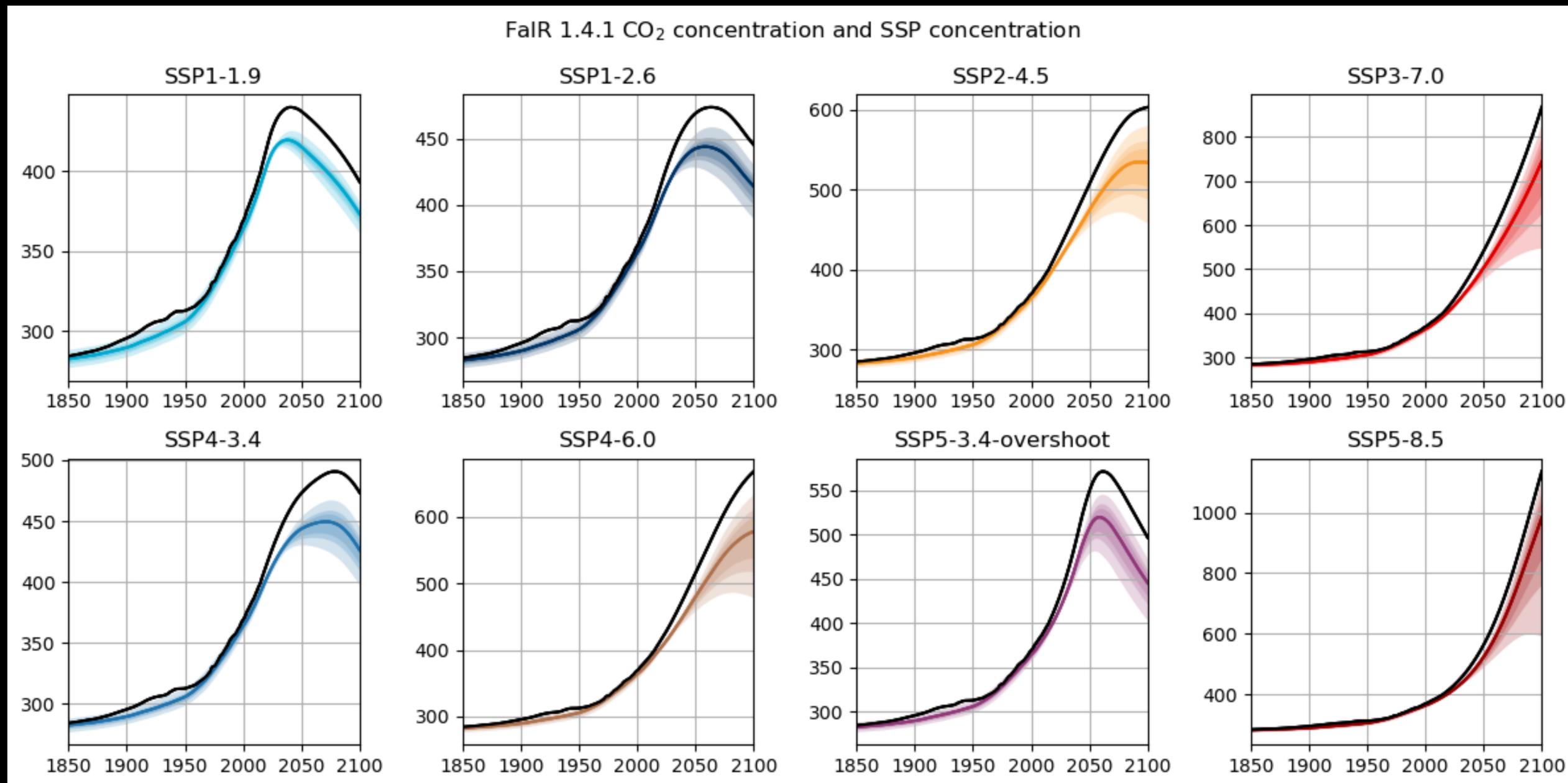


Reduced Complexity Climate Models

- **fair** (Finite Amplitude Impulse-Response Model, Smith et al 2024) is the focus here
 - **Globally averaged!!**
 - 3 mode temperature!
 - 4 timescale carbon cycle!
- MAGICC only has Northern & Southern Hemispheres, and an advective-diffusive ocean
- Very little scrutiny on these models!

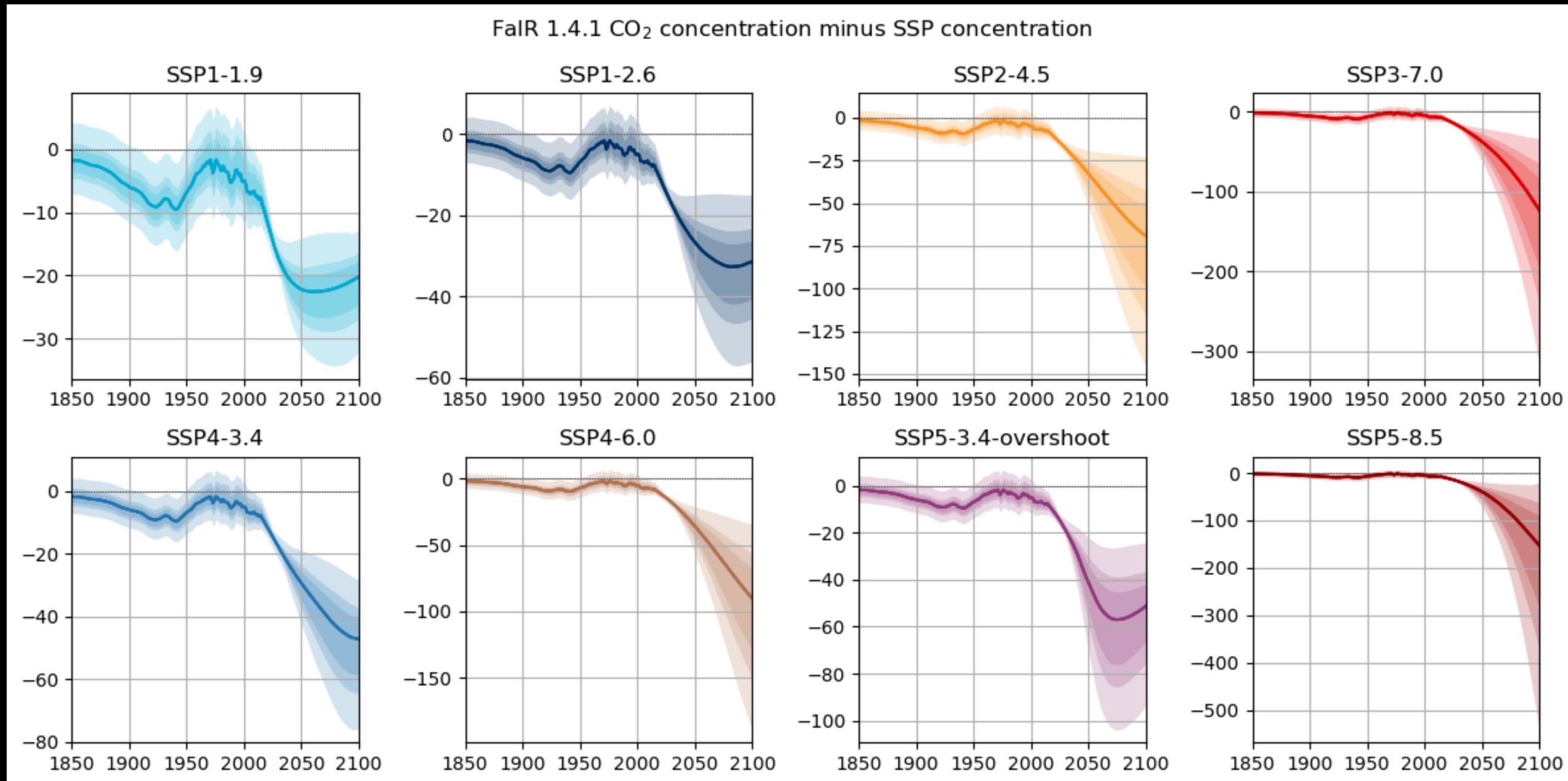
fair doesn't match SSP CO₂ levels

- fair's newest configuration has too low CO₂ in every case

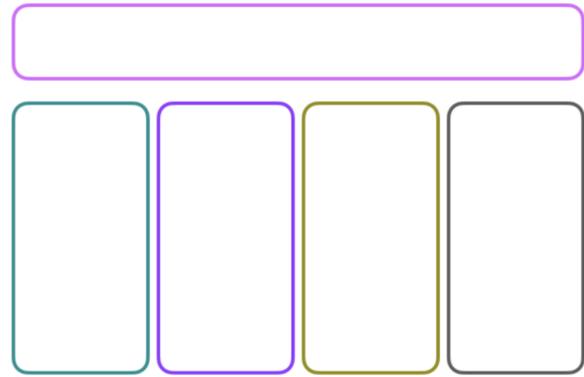


fair doesn't match SSP CO₂ levels

- fair's newest configuration has too low CO₂ in every case



fair's carbon cycle is based on the AR5-IR model



AR5-IR

fair

IPCC AR5-IR carbon cycle based on Joos et al (2013)

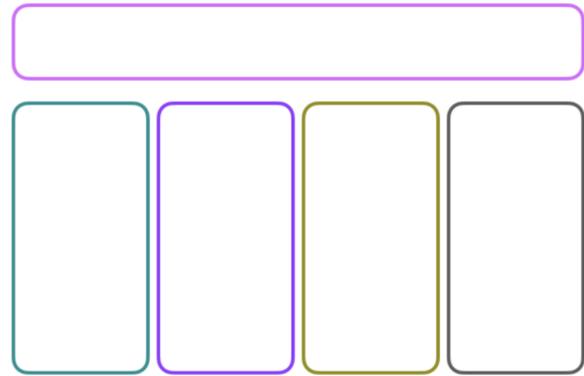
- Tuned to ESMs and simpler models
- Impulse-response functions derived from these models

$$C(t)/P = a_1 + \sum_{i=2}^4 a_i e^{-t/\tau_i}$$

Pool	1	2	3	4
Fraction a	0.2173	0.224	0.2824	0.2763
Timescale τ	infinity	394.4 yrs	36.54 yrs	4.304 yrs
Interpretation	chemical weathering	deep ocean carbon uptake	land carbon uptake	surface ocean carbon uptake

fair carbon cycle

fair adds a lifetime modifier α



AR5-IR

fair

$$C(t)/P = \sum_{i=1}^4 a_i e^{\frac{-t}{\alpha\tau_i}}$$

$\alpha \sim 1$ near 2010 (hopefully, to fit AR5-IR model)

$$I = r_0 + r_u C_{acc} + r_T T + r_A C$$

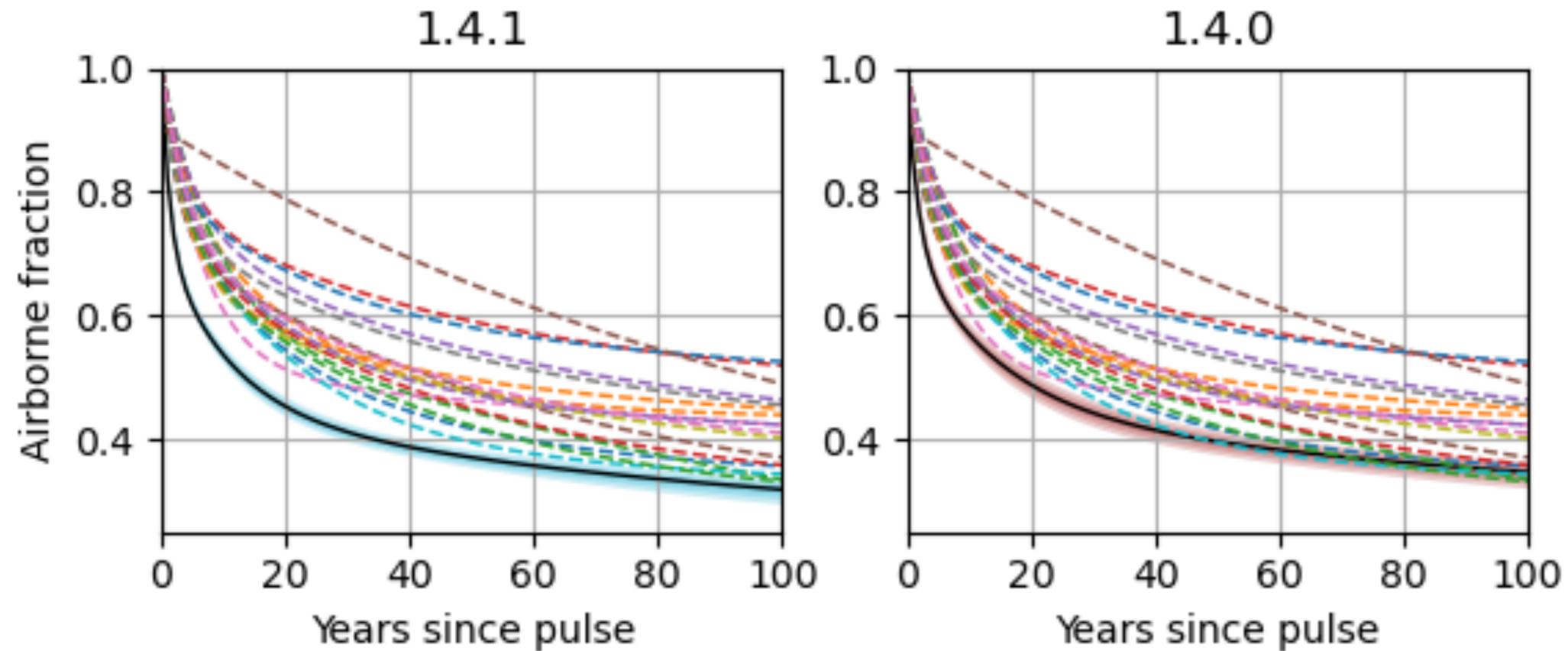
$$\alpha = g_0 \exp(I/g_1)$$

Parameters are varied over plausible range,
those that disagree with observations are discarded

Two recent calibrations, newer in **blue**

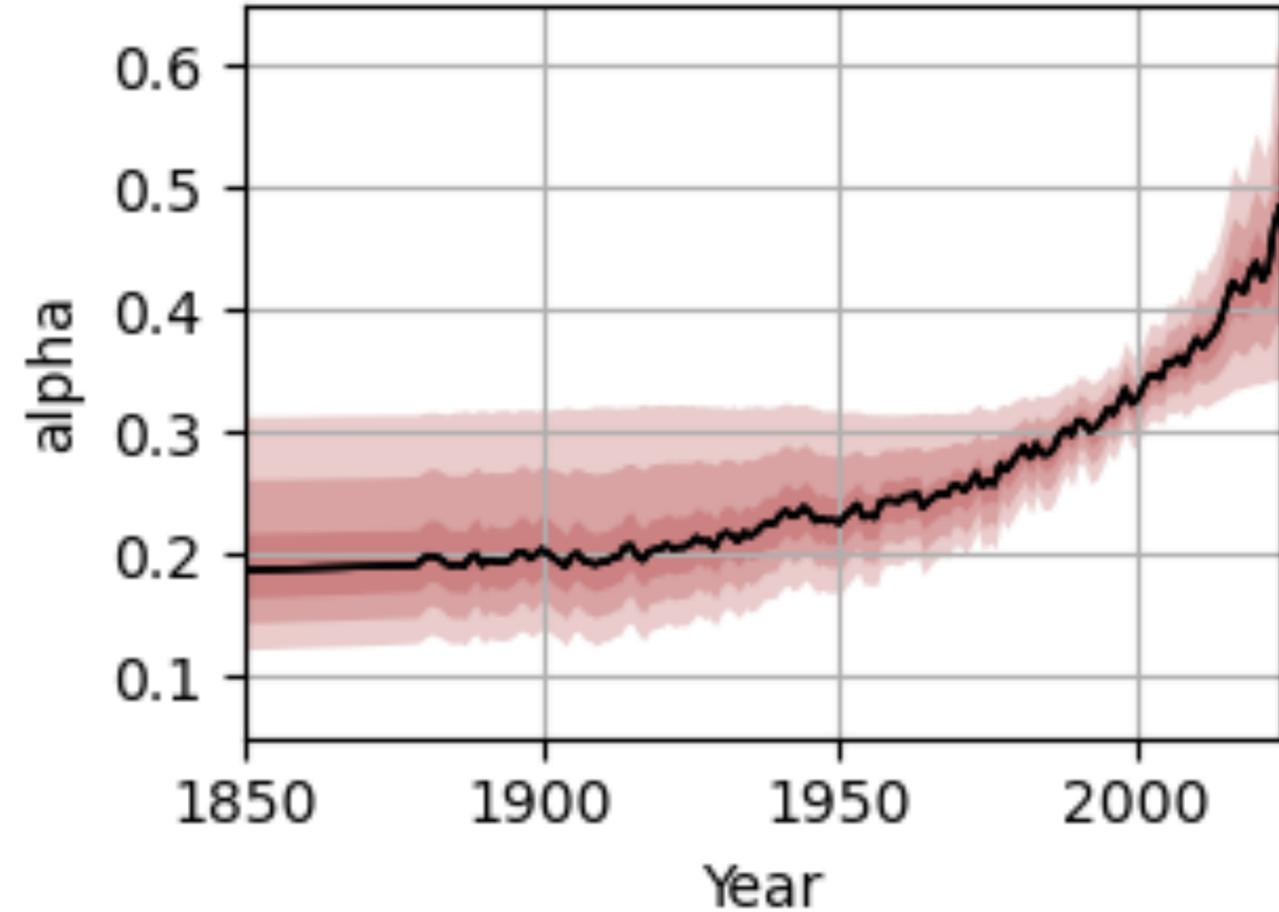
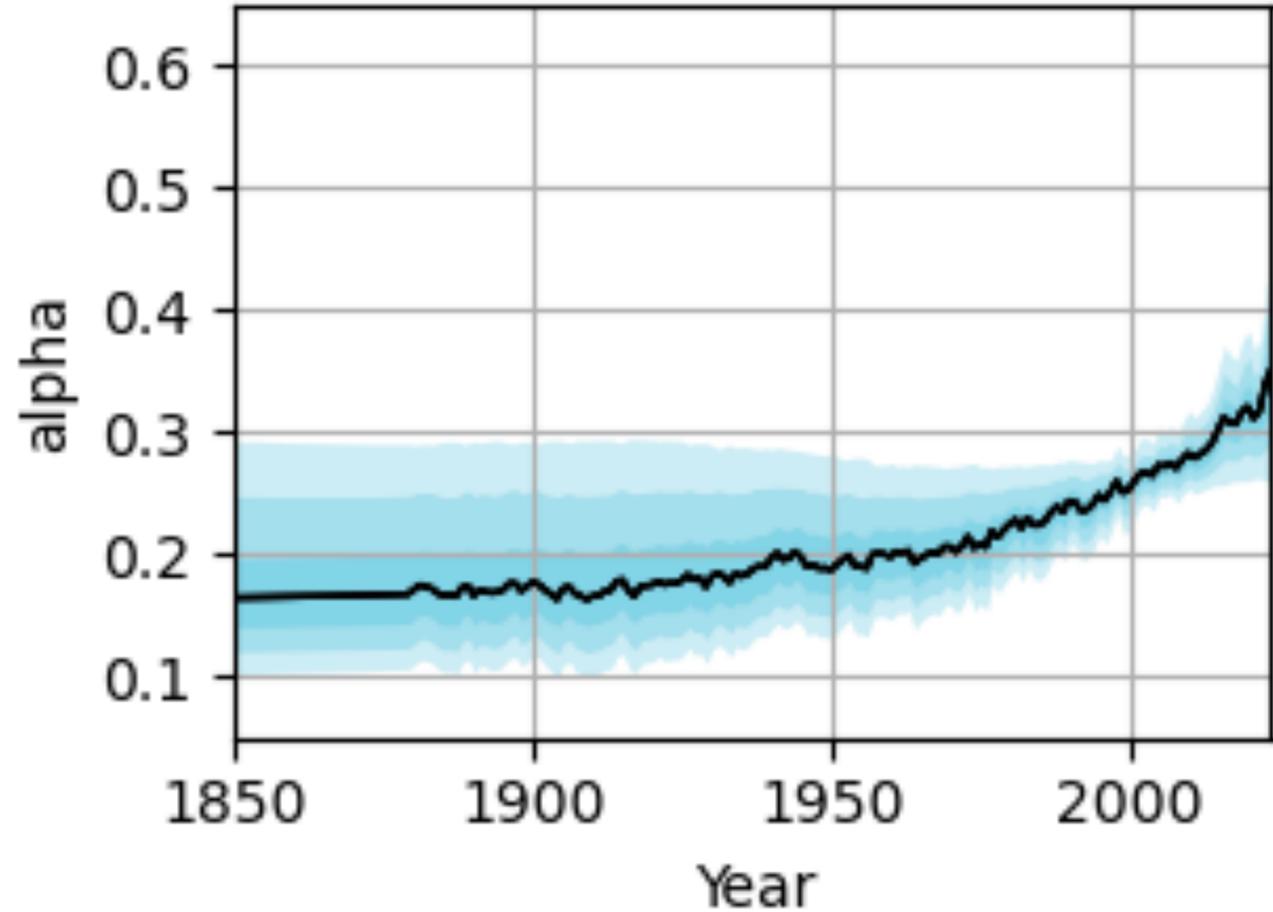
AR5 pulse experiment

- Two calibrations both dissipate pulses too quickly
- Not nearly enough variance



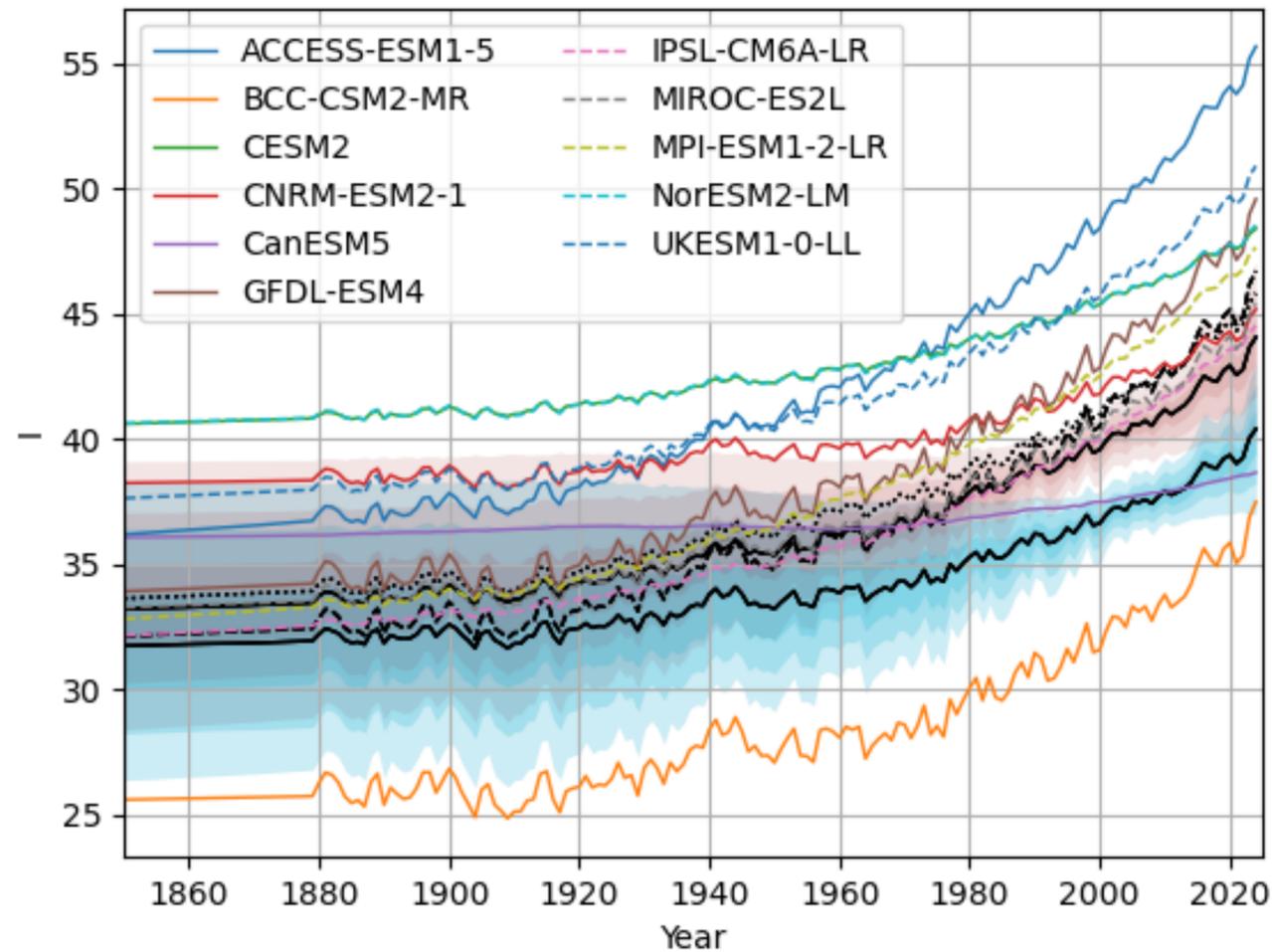
Lifetimes are very short in fair

- α should be near 1 in 2010



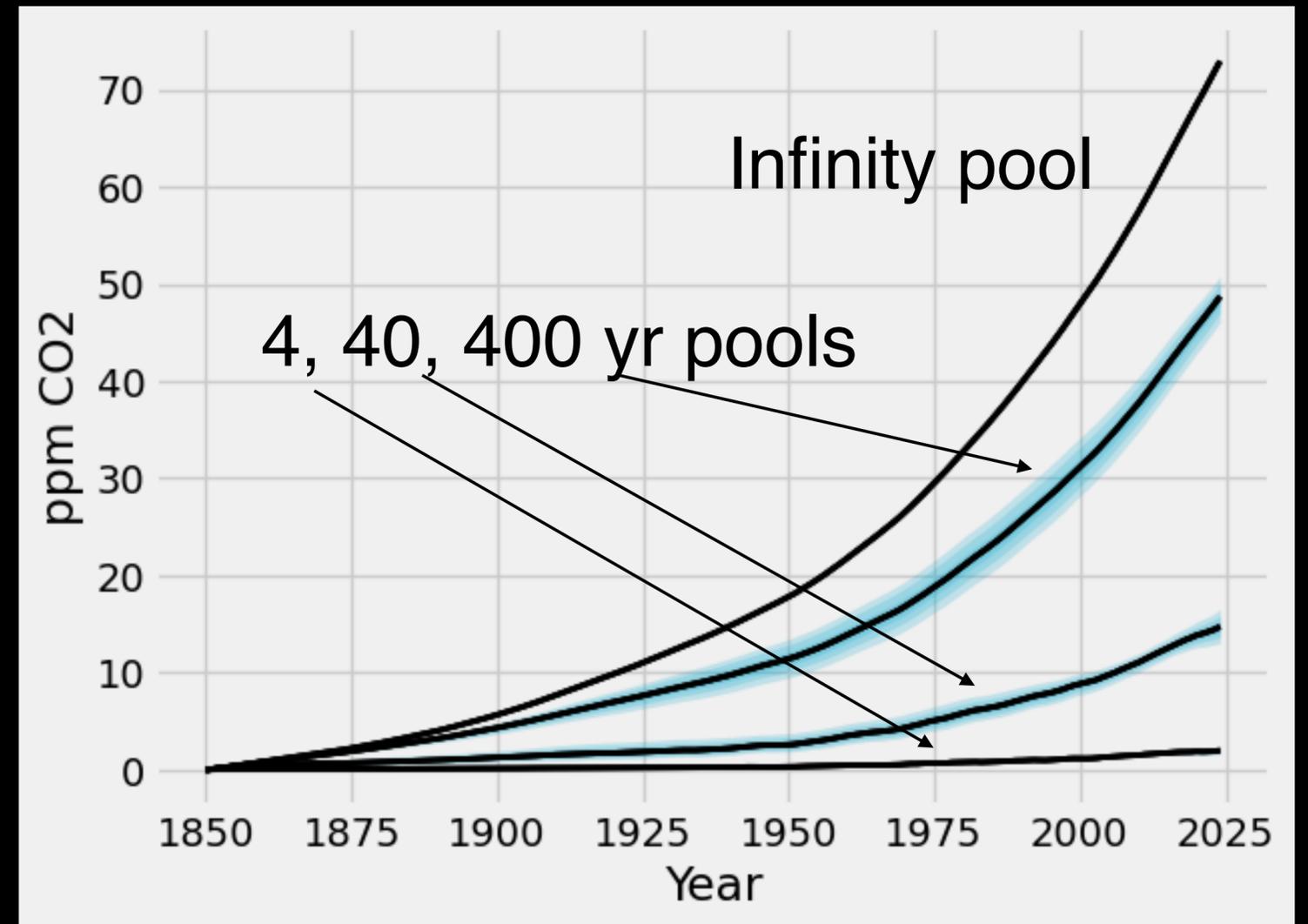
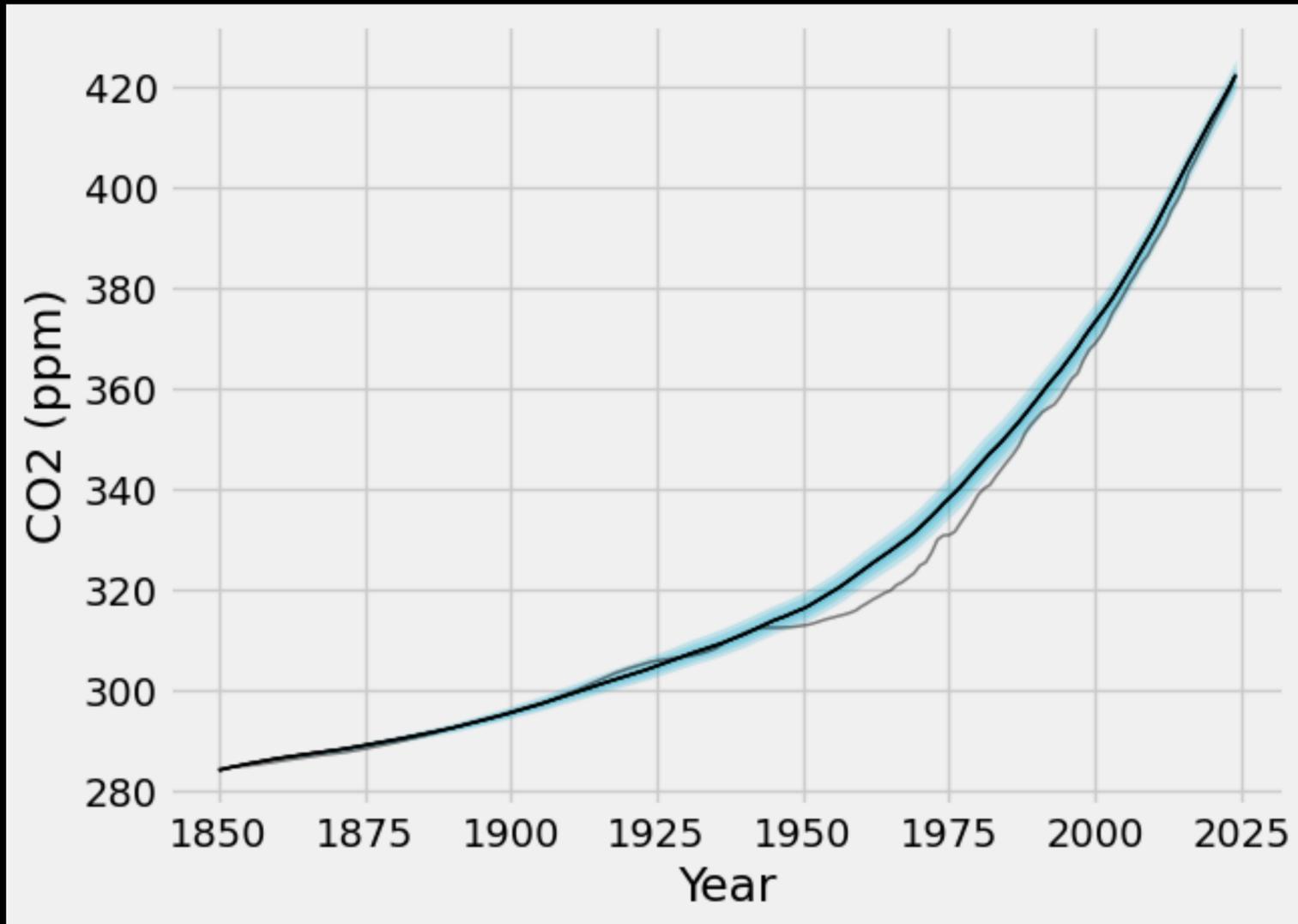
Climate models have much larger range

- I is plotted here, $\alpha \sim \exp(I)$



fair CO₂

- All ensemble members fit current CO₂ concentrations (by construction).
- Most CO₂ is in infinity pool



Infinity pool keeps everything

- Infinity pool equation:
$$\frac{dC_1}{dt} = f_1 E$$

- The solution is
$$C_1 = \int_0^t f_1 E dt$$

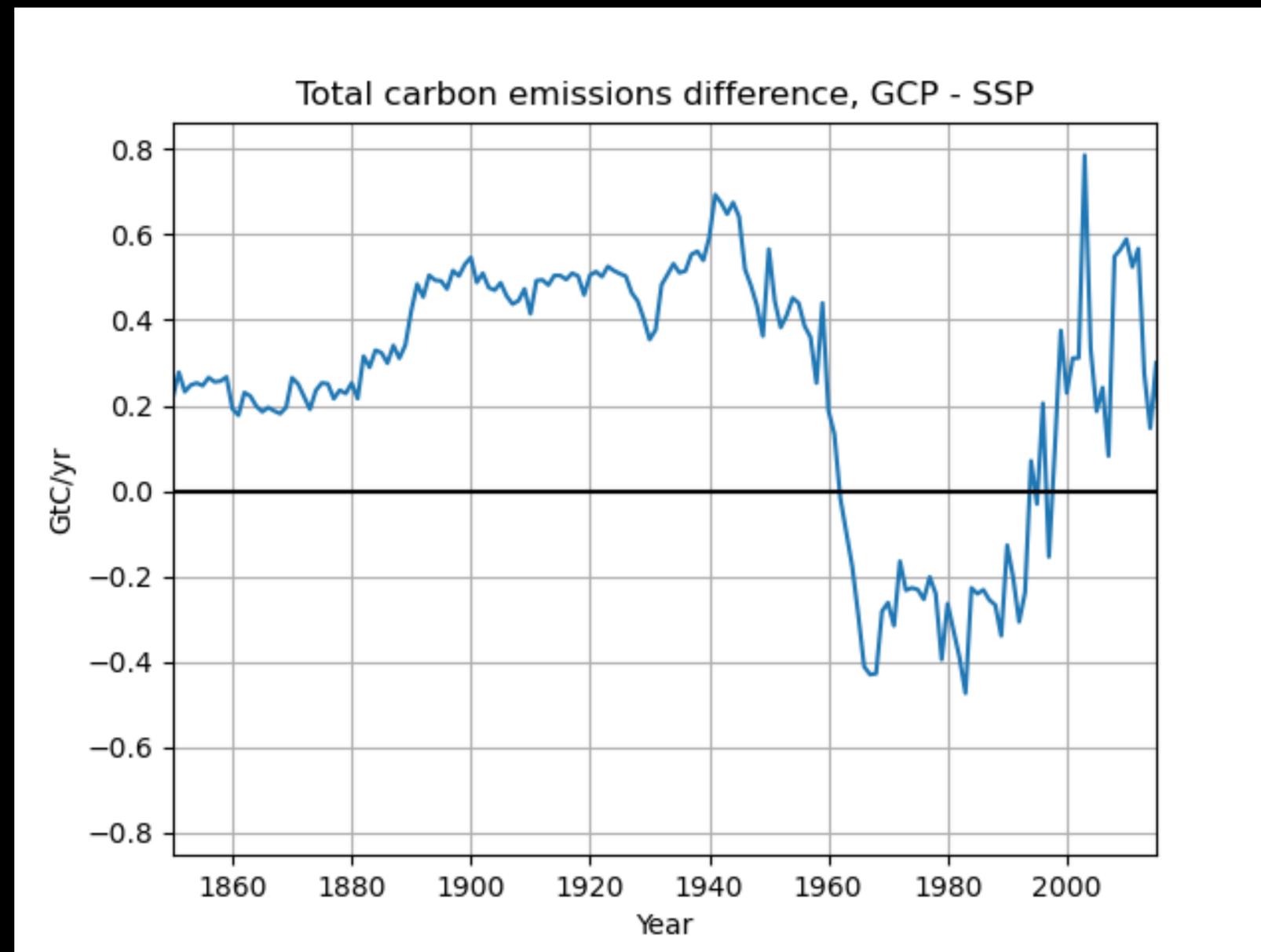


(not this kind of infinity pool)

- 21% of emissions stay in atmosphere forever! (over 70 ppm for historical emissions)
 - However, Joos et al study showed that for perturbations about pre-Industrial state, fraction into infinity box is much smaller!

Upward revision of historical emissions estimates

- Emissions are higher than we thought from 1850-1960



How fair deals with larger emissions

- CO₂ concentration is known extremely accurately from ice cores
- Historical emissions are put in as known, even though there's significant uncertainty
- There's very little room for different alpha values near when the emissions happen
- When emissions are larger, timescales must shorten substantially for other boxes
- This gives a quantitative explanation for the lifetime reductions

One other use of fair: climate accountability

- Who is to blame for climate change?

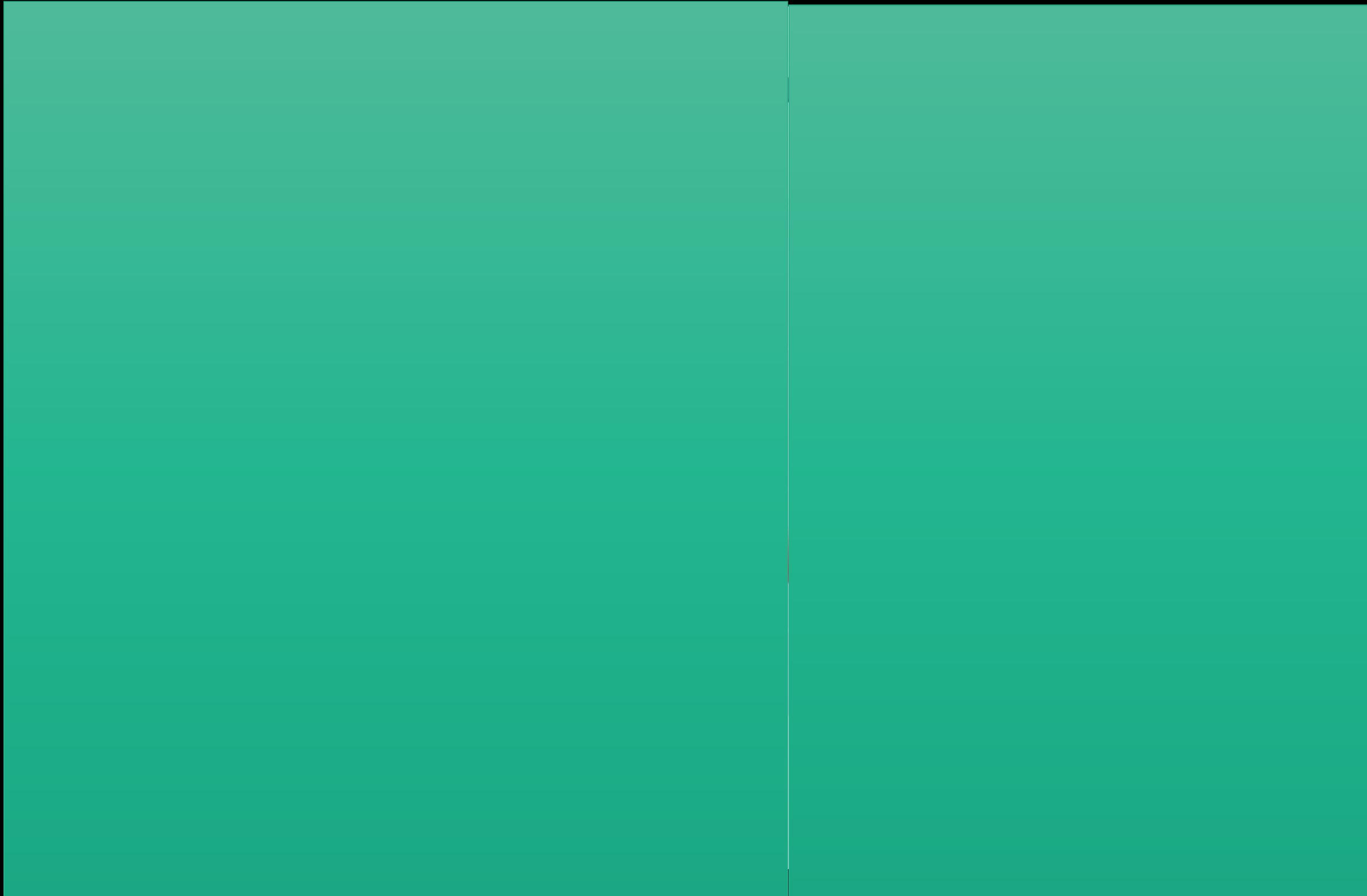
“There is general scientific agreement that the most likely manner in which mankind is influencing the global climate is through carbon dioxide release from the burning of fossil fuels”

- Exxon scientist James Black to top management

What year?

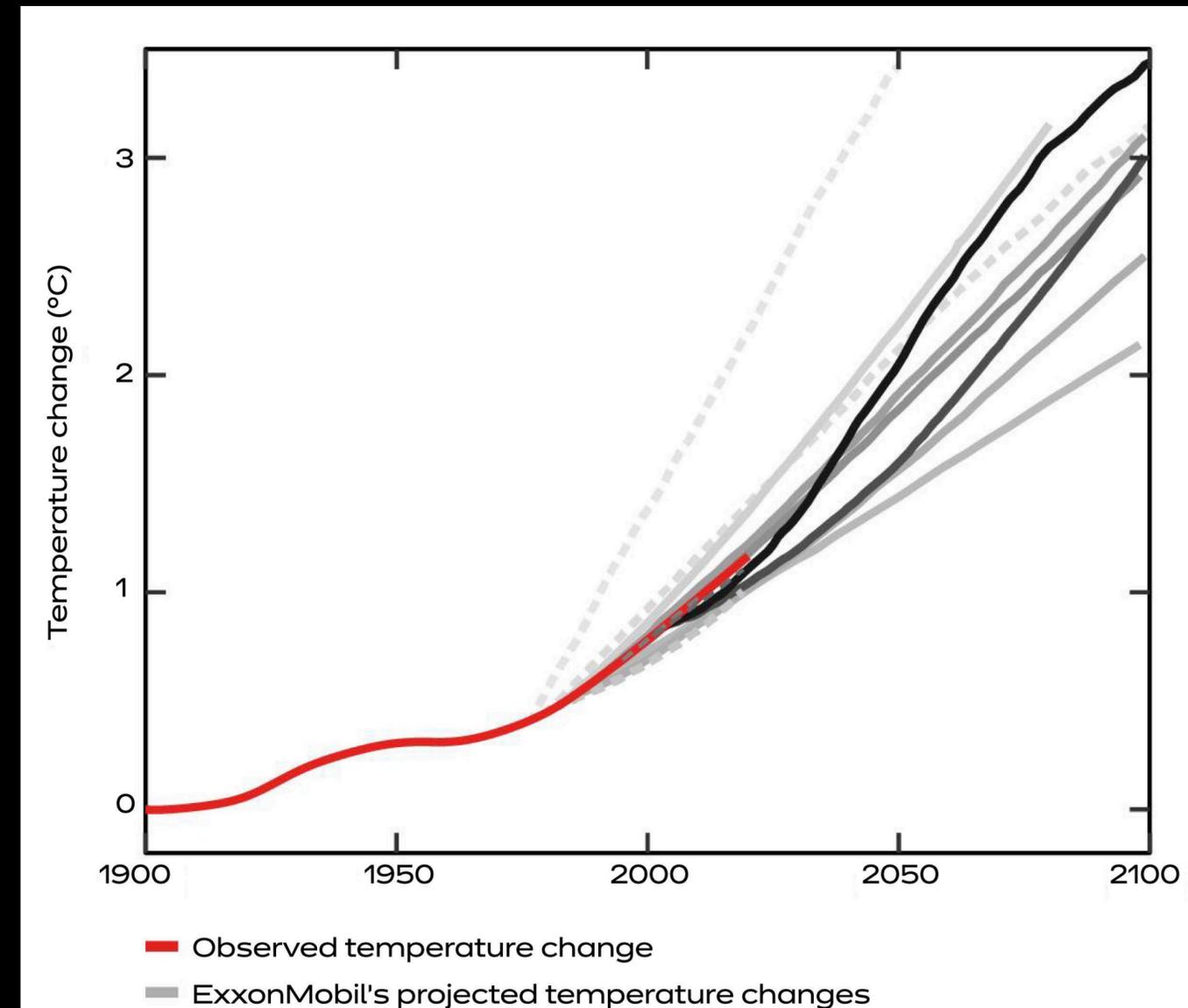
The Exxon logo is displayed in a white rectangular box with a blue border. The word "EXXON" is written in a bold, red, sans-serif font. Below the text is a solid blue horizontal bar.

What's happened to the climate since 1977?



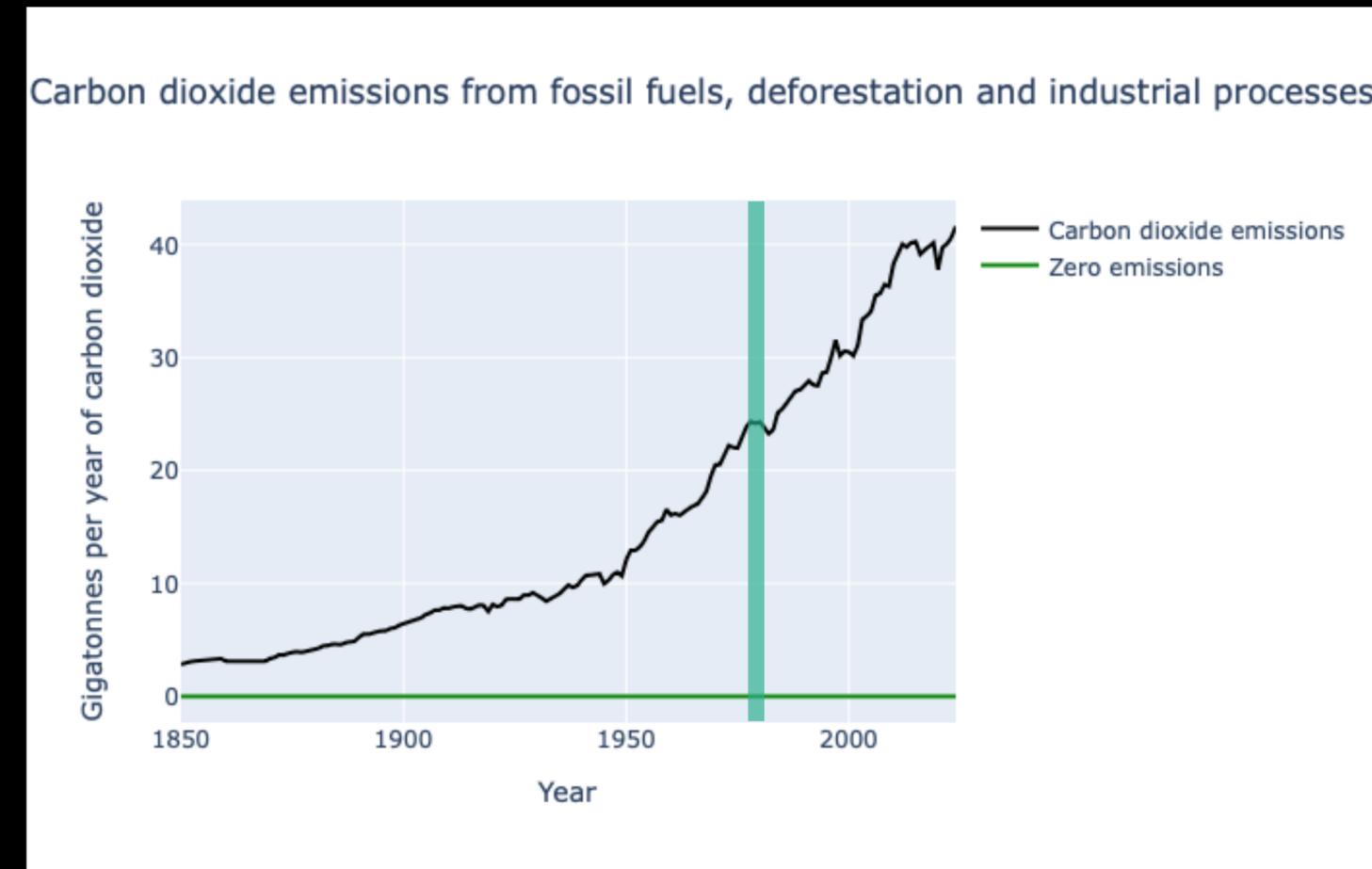
Exxon did research on climate science!

- Had a research program in the 1980s doing climate modeling & measuring carbon dioxide in the air
- Made quite accurate predictions >>>
- Came to same conclusions as university and government scientists



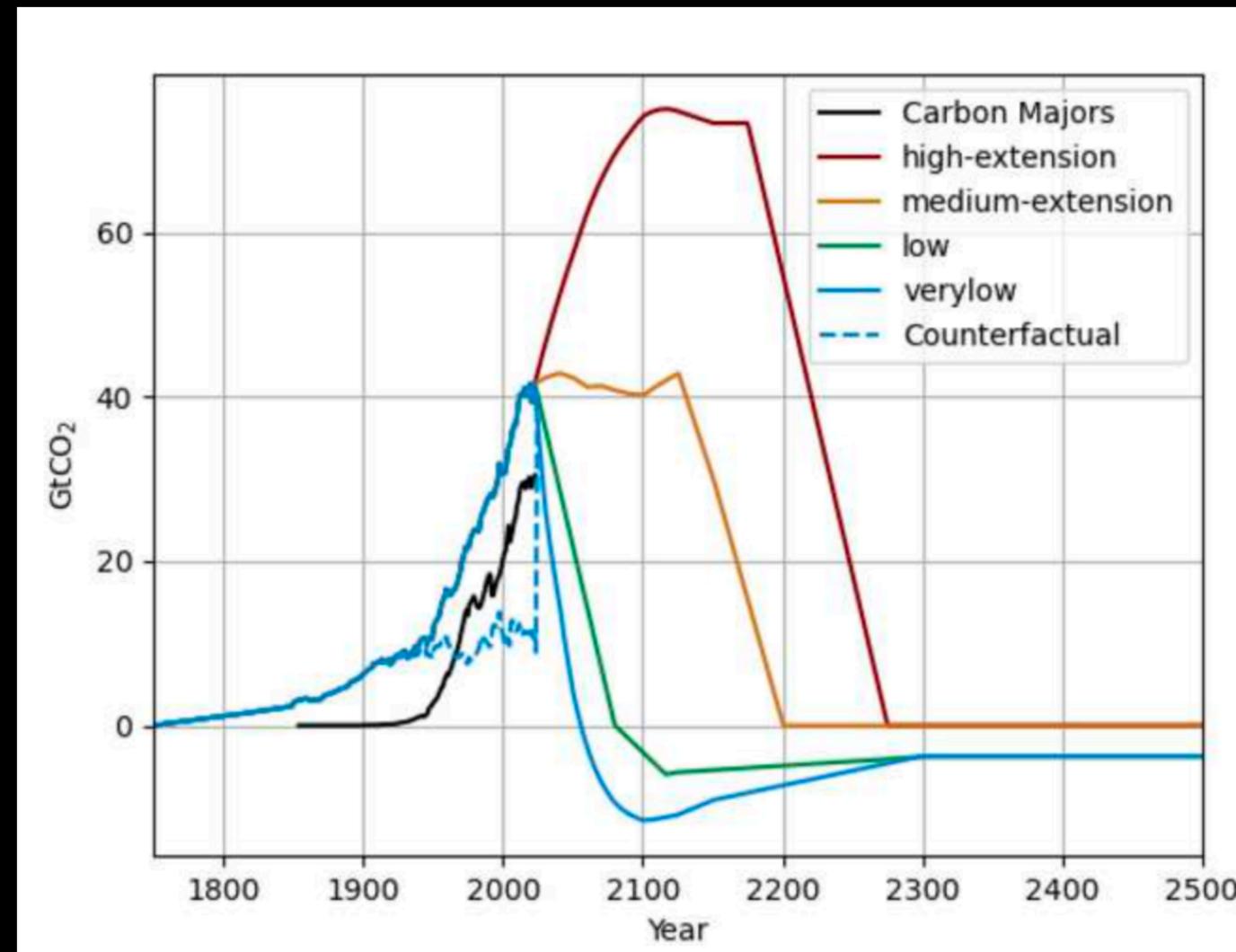
An Abrupt Shift

- In the late 1980s, Exxon abruptly eliminated their research program and started funding climate denial
 - Climate “doubt factories” were key to shaping public opinion over following decades
- Fossil fuel burning soared
 - More fossil fuels have been burned since then than in all of history beforehand



Accountability Simulations

- Counterfactual experiment subtracting out Carbon Majors dataset

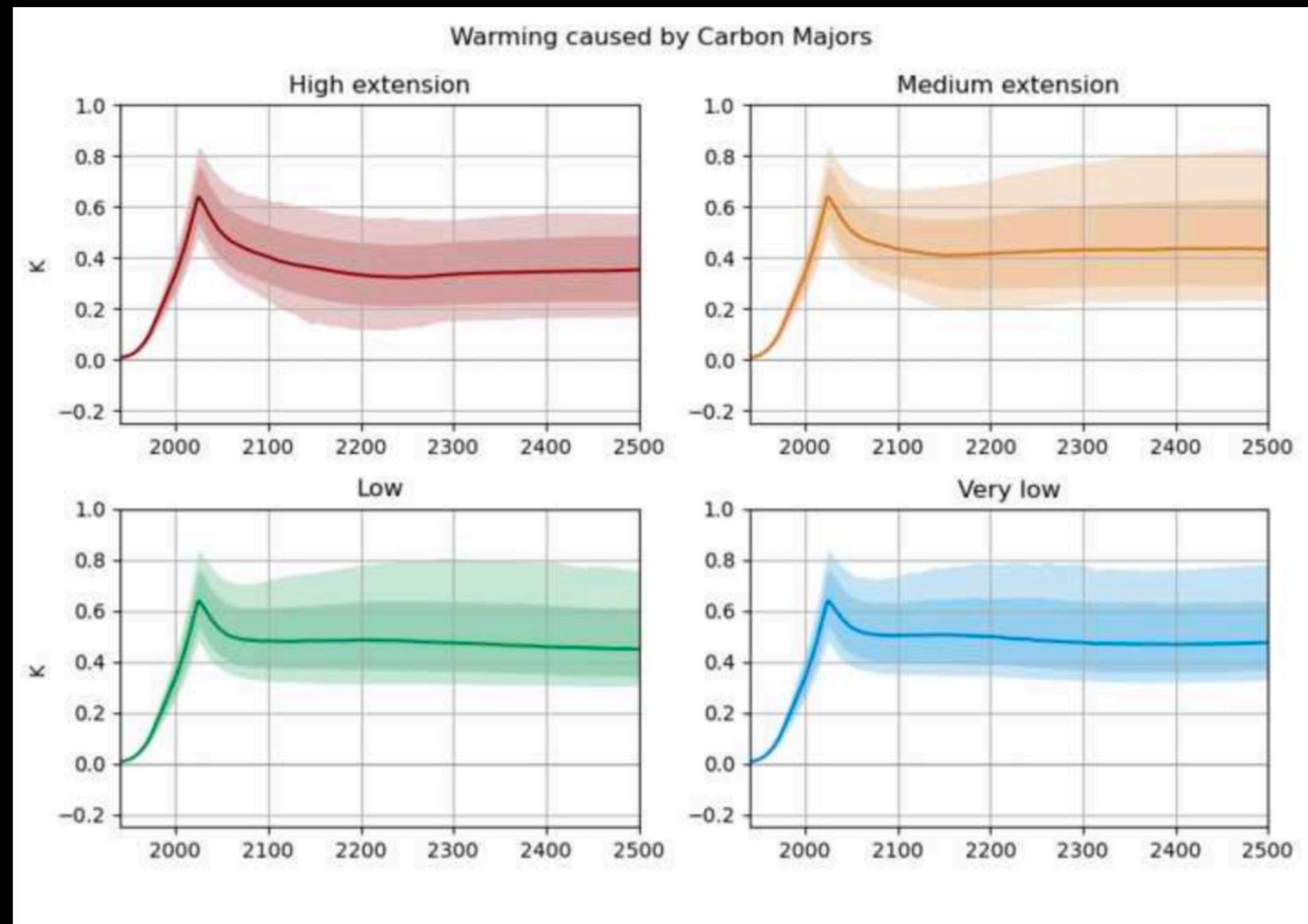


1750

2500

Accountability Simulations

- **Temperature change lasts hundreds of years**



High

Medium

Low

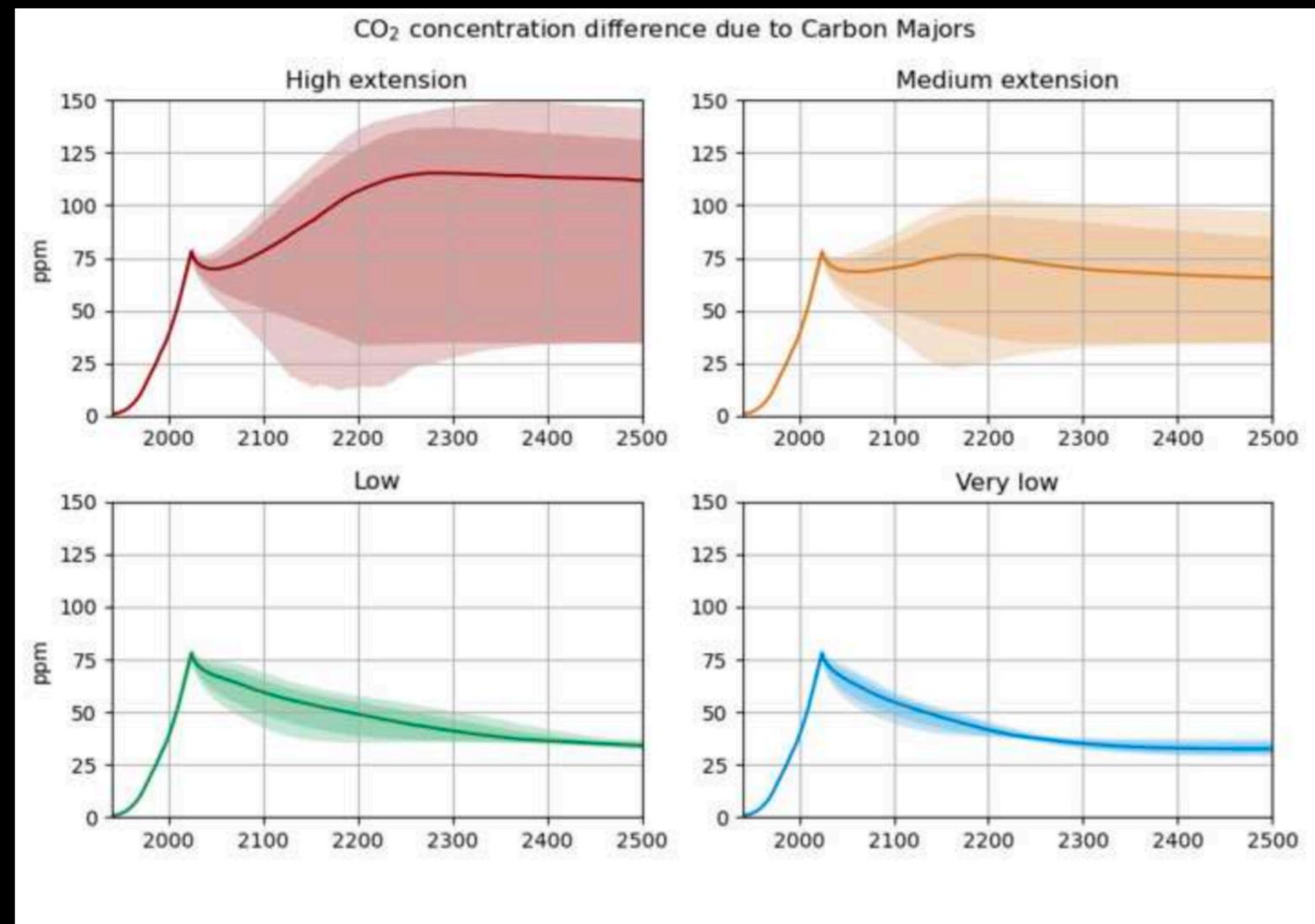
Very low

Accountability Simulations

- **CO₂ change** is larger in high emissions simulations

High

Low



Medium

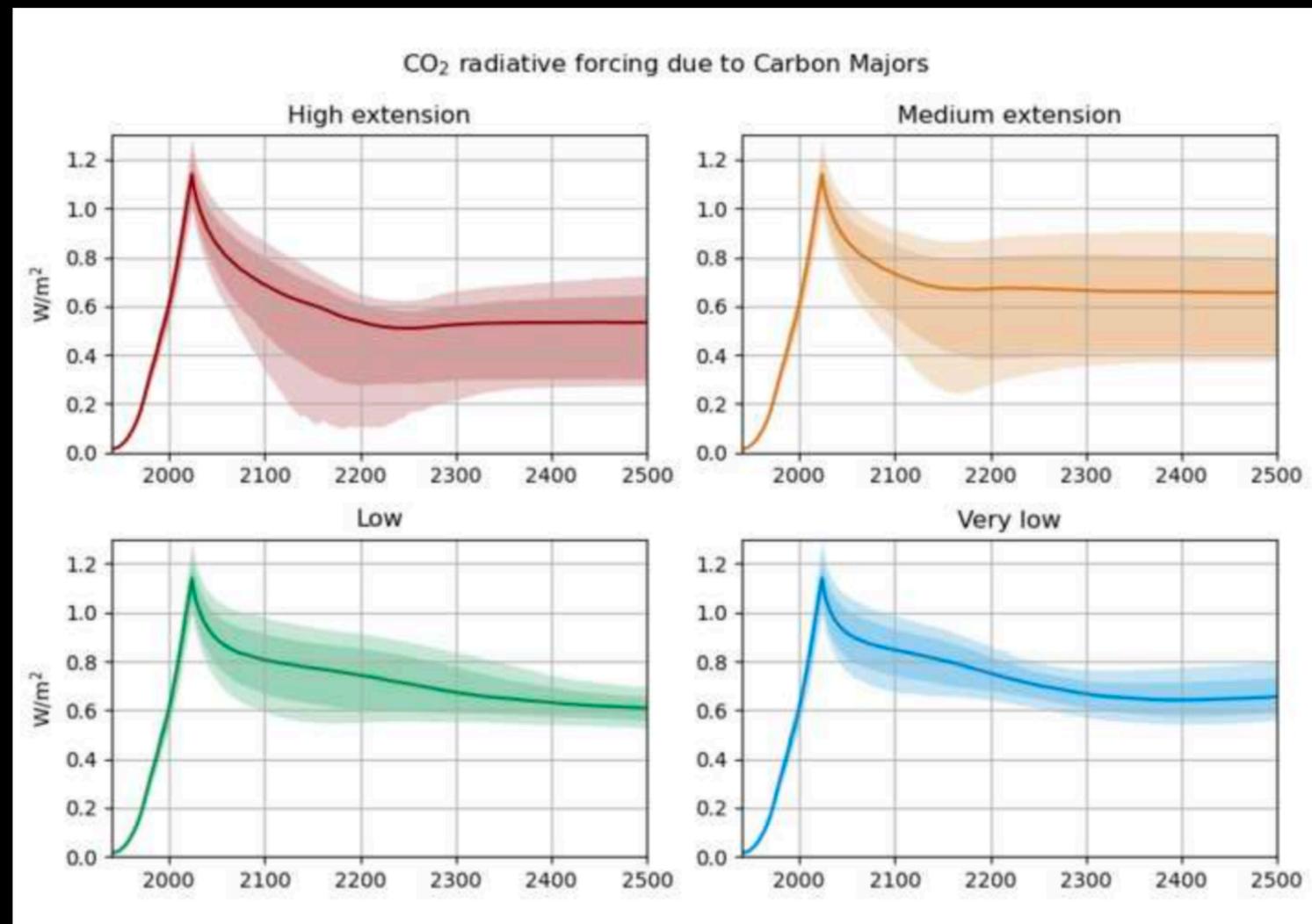
Very low

Accountability Simulations

- **Radiative forcing change is more similar due to logarithmic sensitivity**

High

Low



Medium

Very low

Conclusions

- There can be many possible futures! Let's imagine them together
- Check out the book for more interactive simulations
- Be careful when tuning simple models
- Models can be used to support legal action against polluters