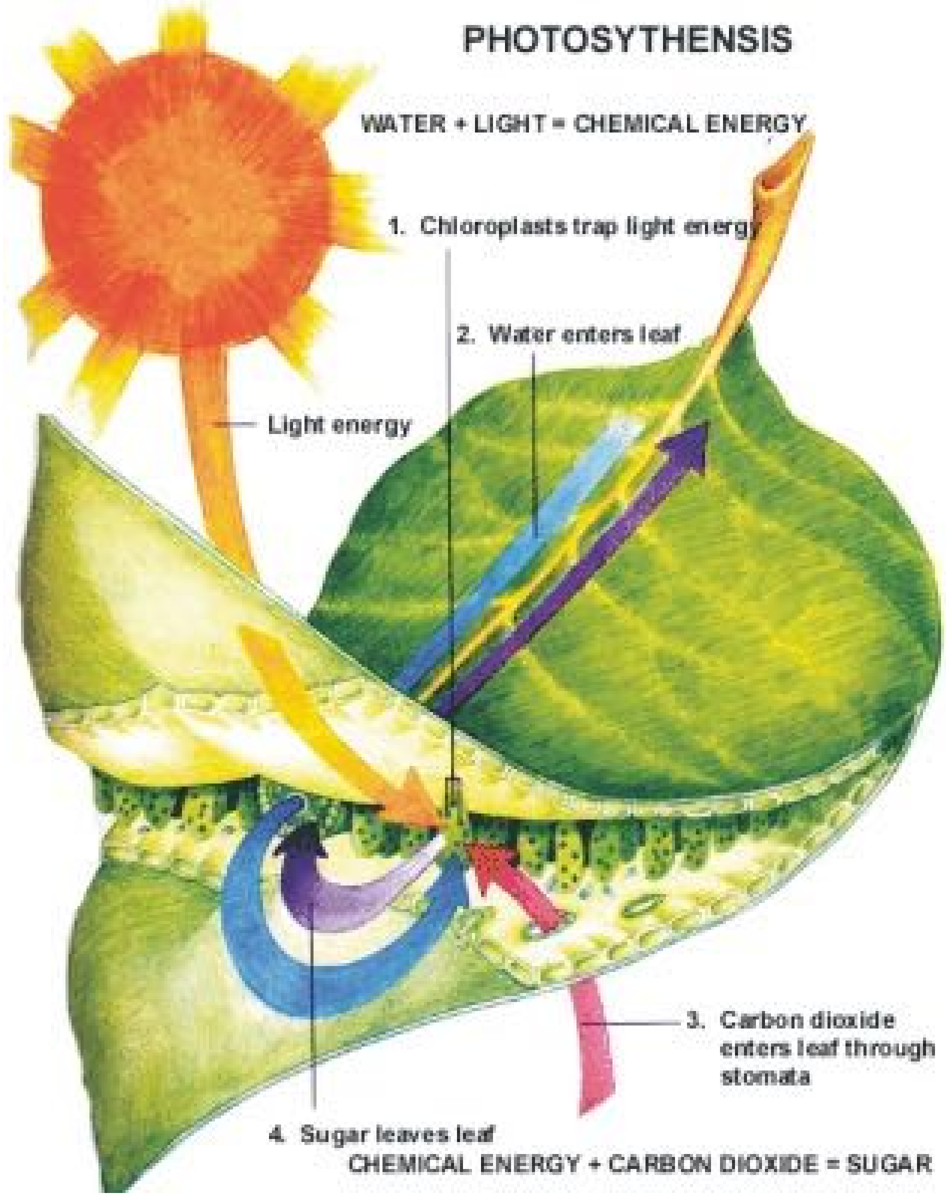
Fate of CO_2

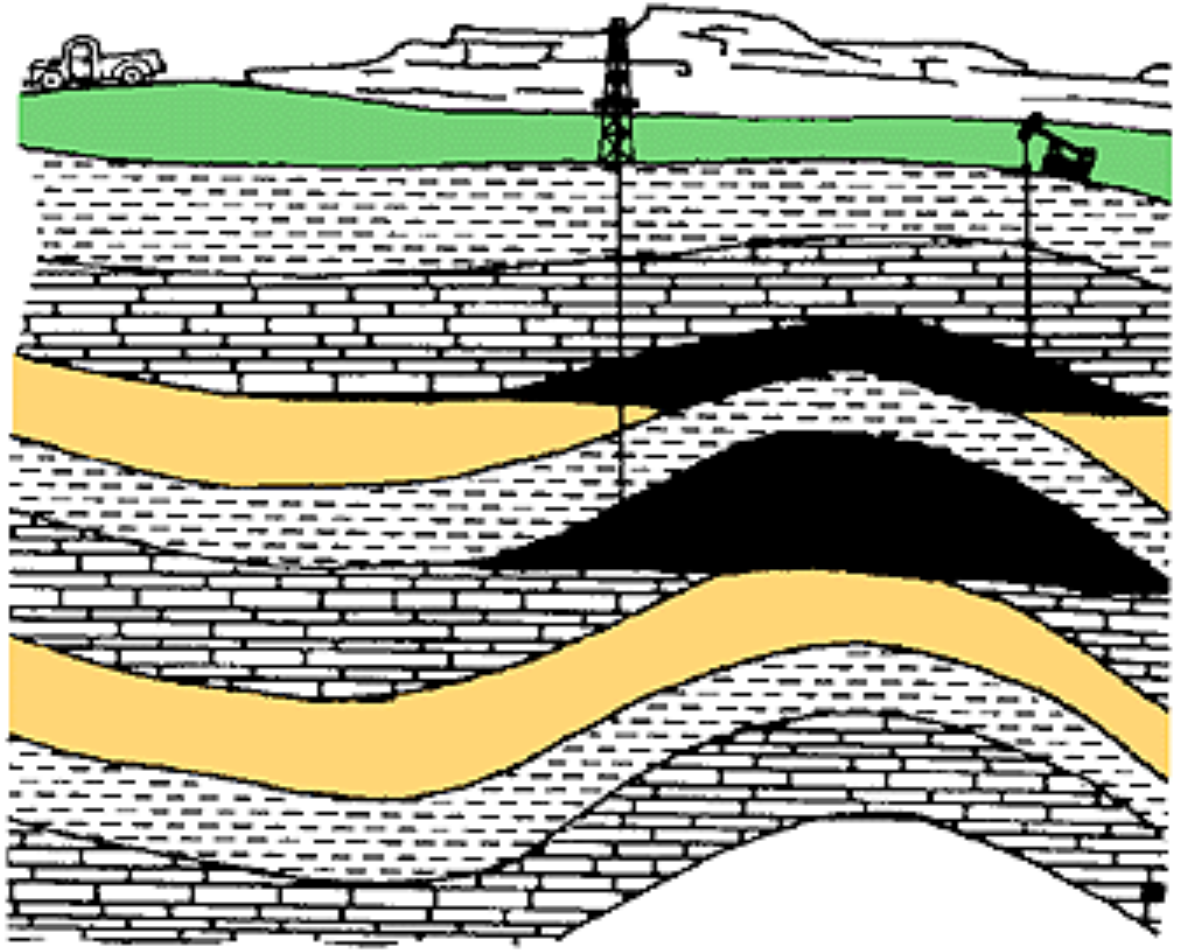
Module 9

Carbon, Life, & Energy



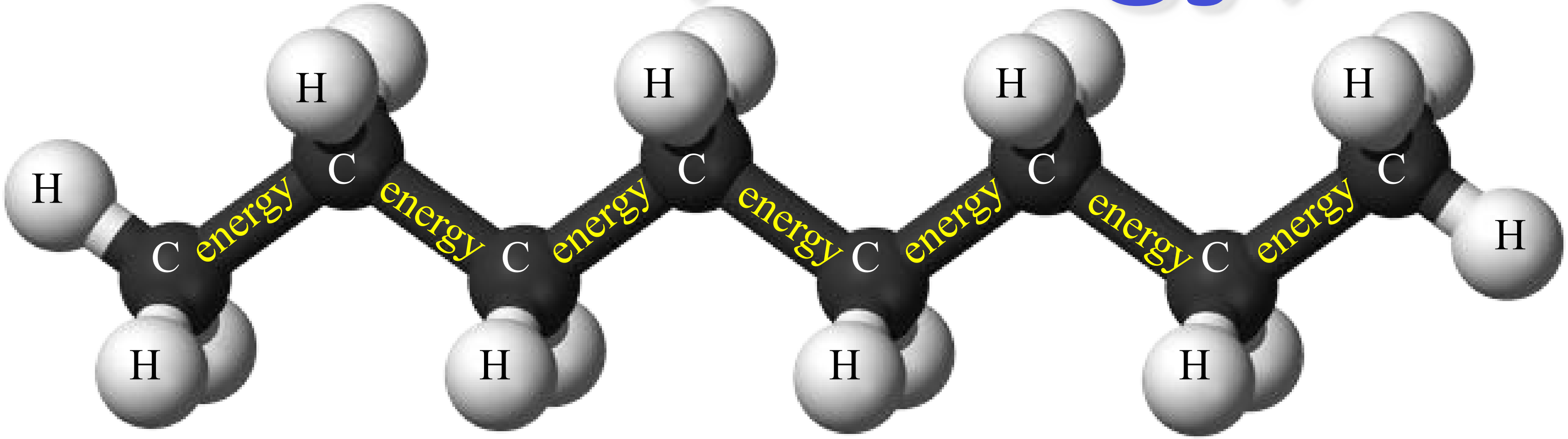
- Photosynthesis uses energy from the sun to convert inorganic air (CO_2) to living biomass!
- Most of this energy is released through respiration (back to CO_2) when plants are eaten by animals, bacteria, people
- 1/7 of all CO_2 every year!

Fossil Fuels

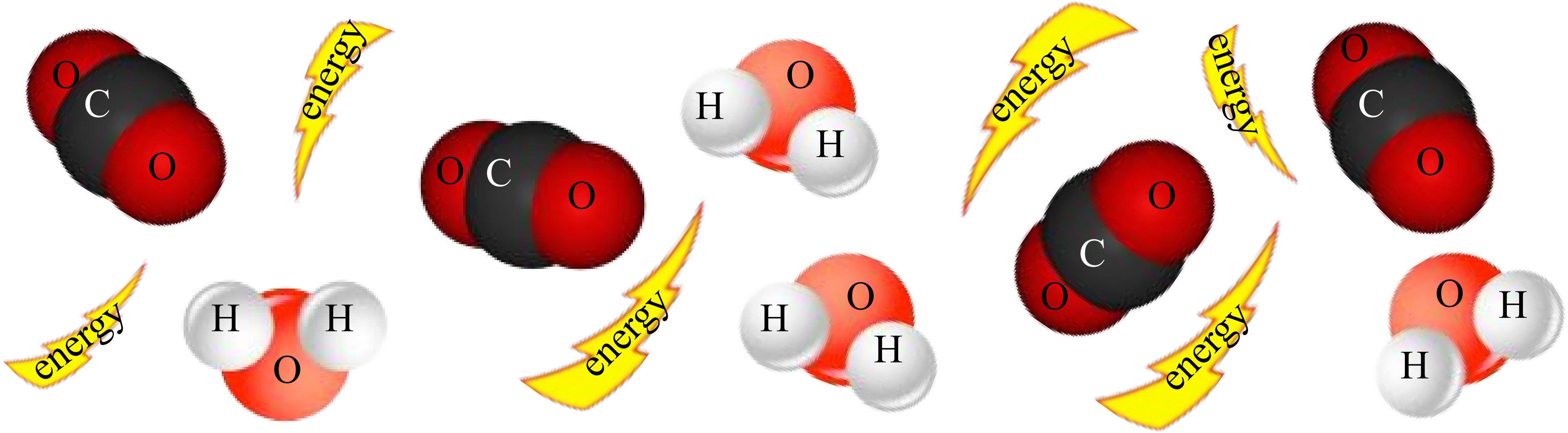


Some of the stored solar energy in biomass can be preserved in fossilized remains

Hydrocarbons, Energy, and CO_2



We dig this stuff ("fossil fuels") up and burn it, harvesting the stored energy to power civilization



The "Missing Sink"

Fossil Fuel Burning	100%

← Commercial Records

The “Missing Sink”

Fossil Fuel Burning	100%	Commercial Records
Atmospheric Increase	50% ←	Direct Measurement

The "Missing Sink"

+	Fossil Fuel Burning	100%	Commercial Records
-	Atmospheric Increase	50%	Direct Measurement
-	Ocean Uptake	25%	← Bomb ^{14}C

The "Missing Sink"

+	Fossil Fuel Burning	100%	Commercial Records
-	Atmospheric Increase	50%	Direct Measurement
-	Ocean Uptake	25%	Bomb ^{14}C
=	"Missing Sink"	25% ←	Arithmetic

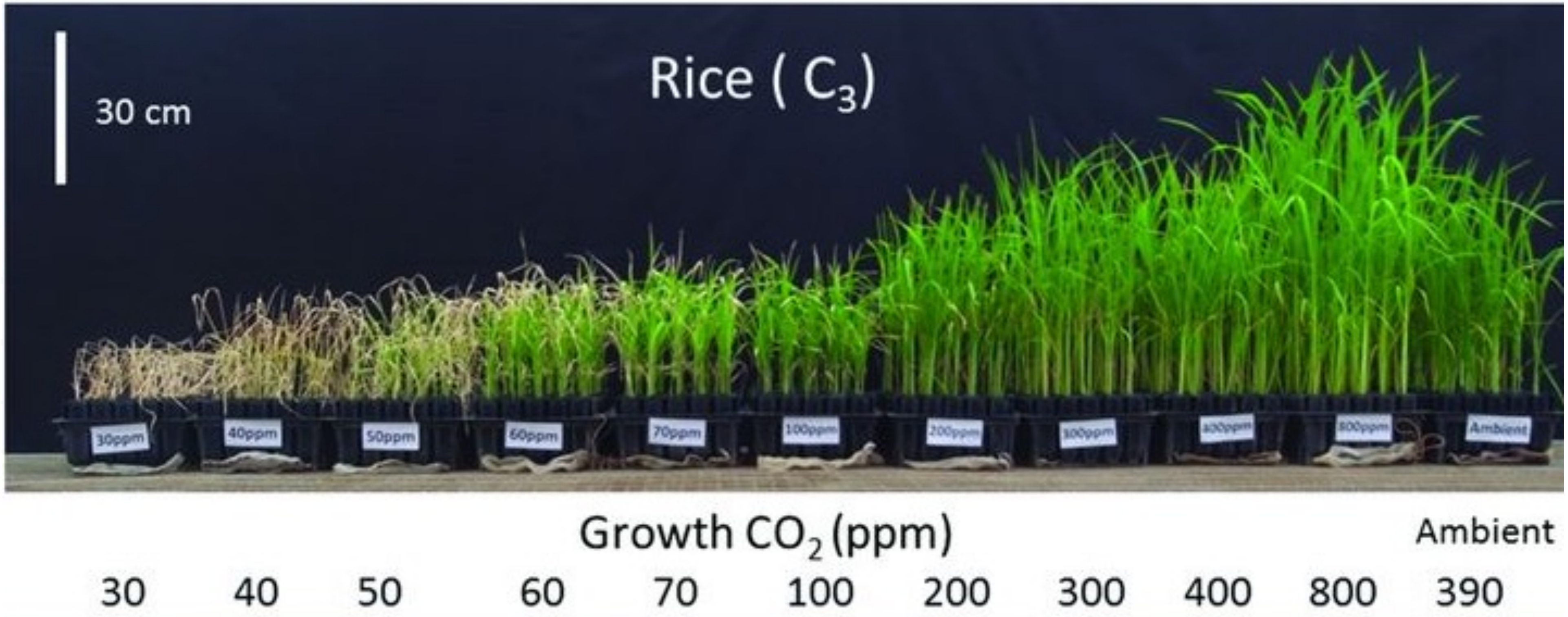
Land Carbon Uptake

Land Carbon Sink?

- Plants eat CO_2 for a living (photosynthesis) …
- Does adding CO_2 to the air make them bulk up?
- Just like adding Girl Scout cookies to my house!

CO_2 "Fertilization"

- Adding CO_2 does make plants grow faster in laboratory or greenhouse conditions, but
- That doesn't necessarily explain missing sink!



All Things Must Pass

- Plants die.
- Eventually ~ everything is eaten by microbes, which respire 100% of the carbon back to CO_2

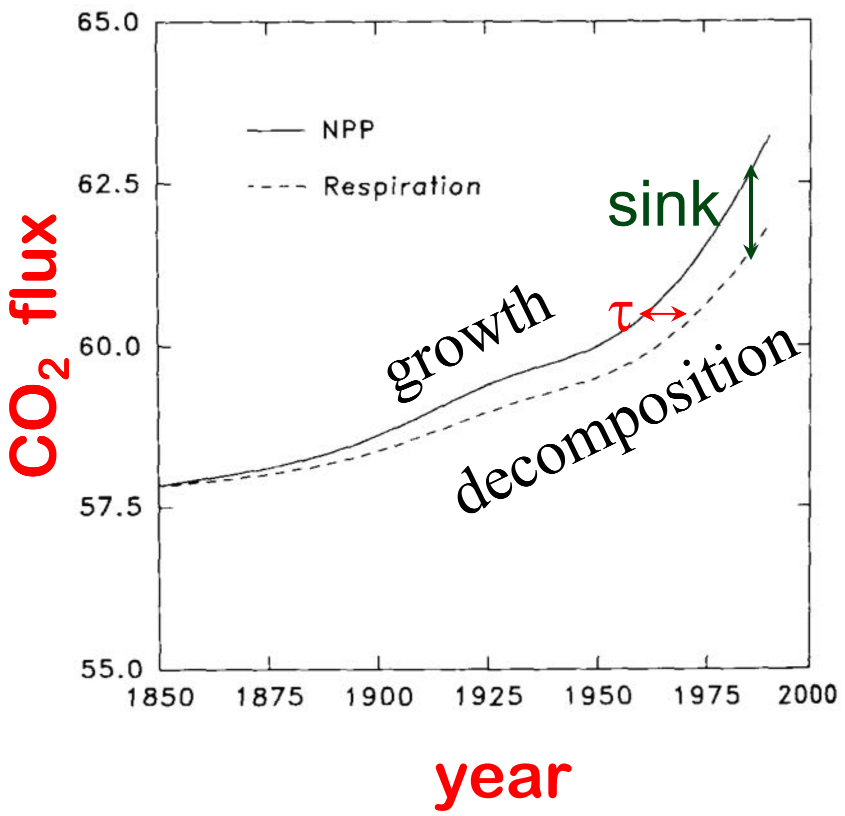
Longstanding Imbalance

- When we say there is a carbon sink on land, we're saying that over many decades

"Plants are growing faster than they're dying"

- Not true everywhere, but it's true of the Earth as a whole!
- Since good measurements began in the 1950's, growth minus decay has been ~ 25% of fossil fuel combustion

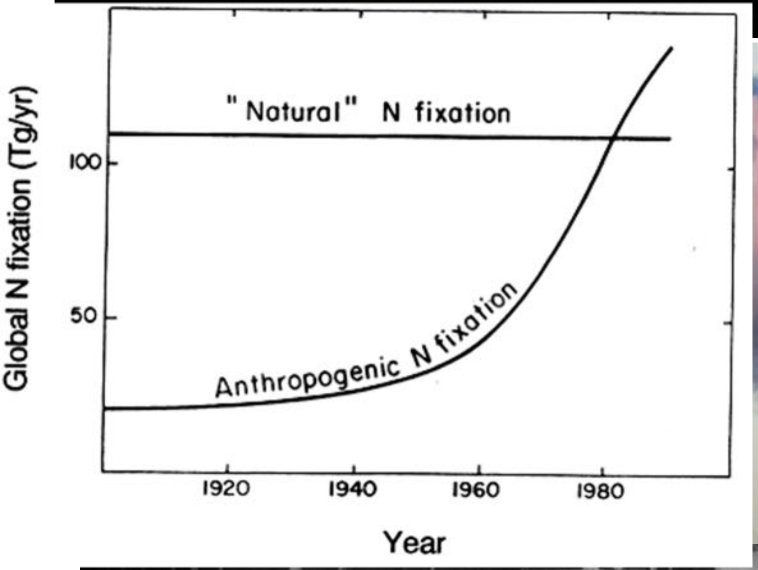
CO_2 "Fertilization"



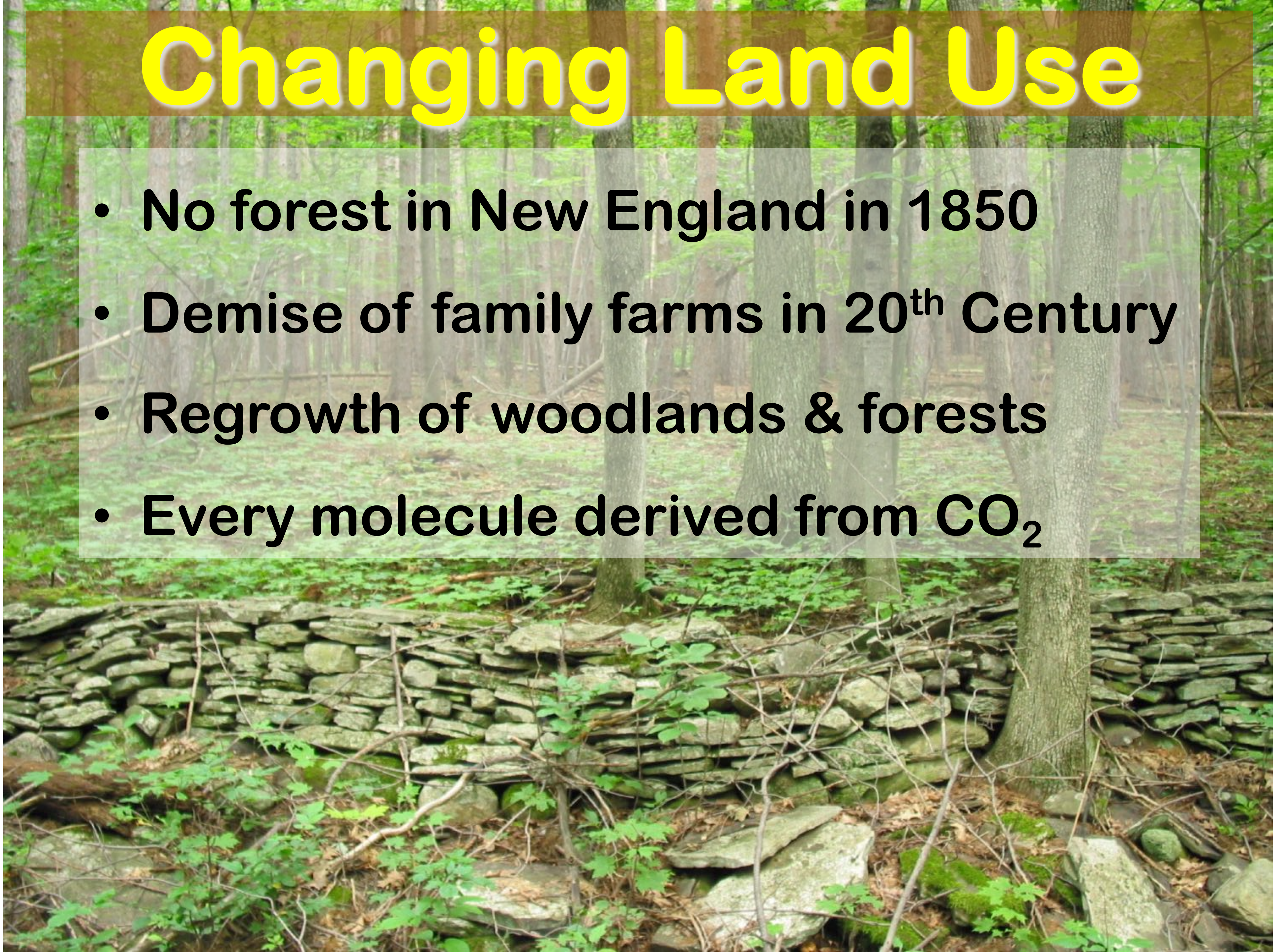
Friedlingstein et al (1996)

- **Increasing plant growth** (photosynthesis) over time due to rising atmospheric CO_2
- Eventually, **respiration increases too** because there's more dead stuff to decay (but it **takes awhile**)
- As long as CO_2 is rising, **growth rate > death rate** in any given year

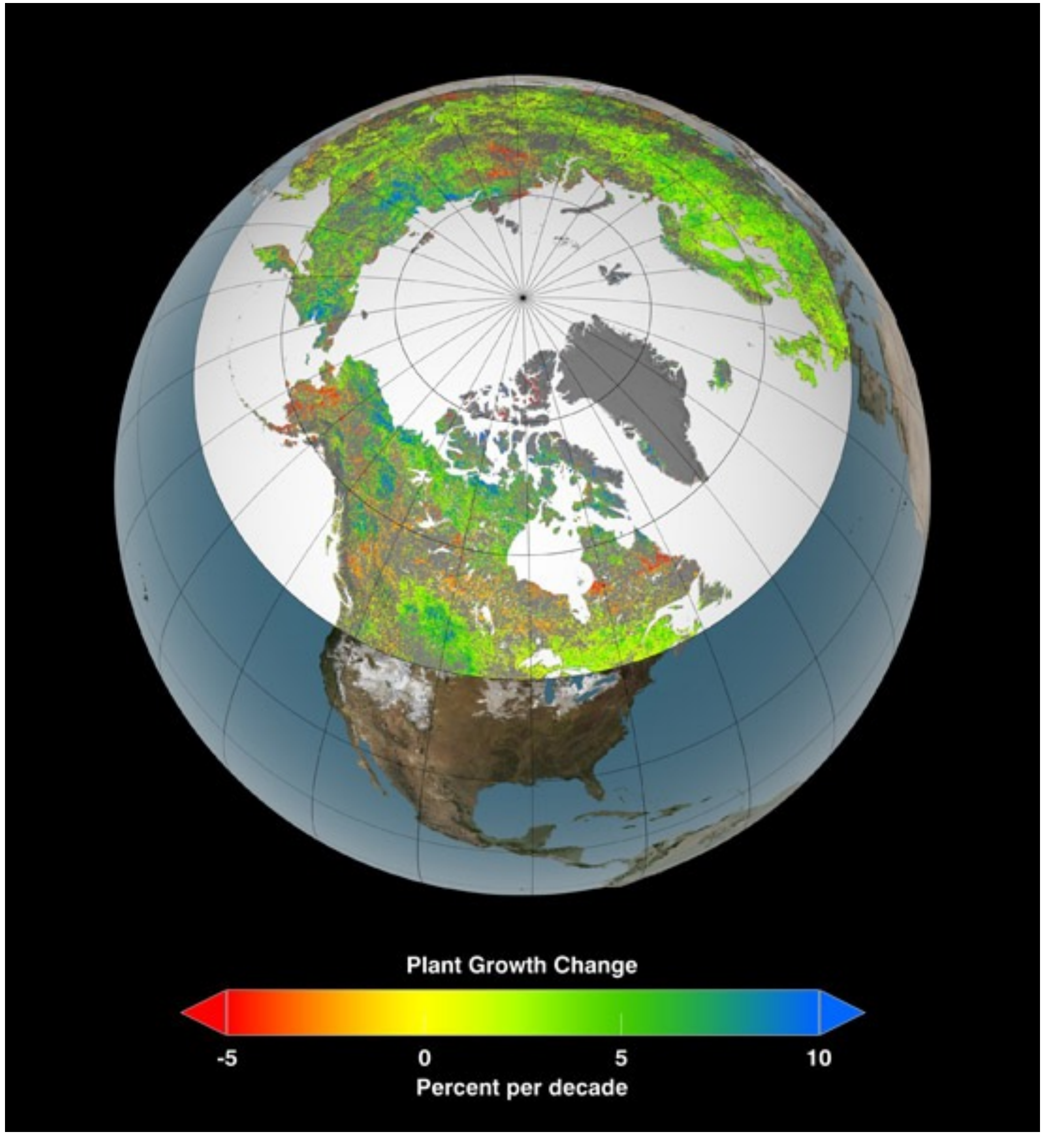
Nitrogen Fertilization



- Atmospheric N_2 is triply-bound so chemically and biologically inert
- Natural N-fixation by lightning and by specialized microbes, linked to very tight N cycling in biosphere
- Manufacture of fertilizers uses energy to fix N
- Combustion burns air!


Changing Land Use
• No forest in New England in 1850
• Demise of family farms in 20th Century
• Regrowth of woodlands & forests
• Every molecule derived from CO_2

Boreal Warming & Greening



- Arctic is warming more than twice as fast as the world as a whole
- Many places have 50% longer growing season than 50 years ago
- Shrubs invade tundra, forest spreads north


The
Oceans

Carbonic Acid

- CO_2 dissolves in water to make carbonic acid
- That's why beer goes with pizza and Chardonnay goes with Brie
- Dissolves twice as well in cold water as warm water
- That's why beer & soda go flat when they warm up
- Cold polar ocean soaks up CO_2, warm tropical oceans release it

Dark and Deep

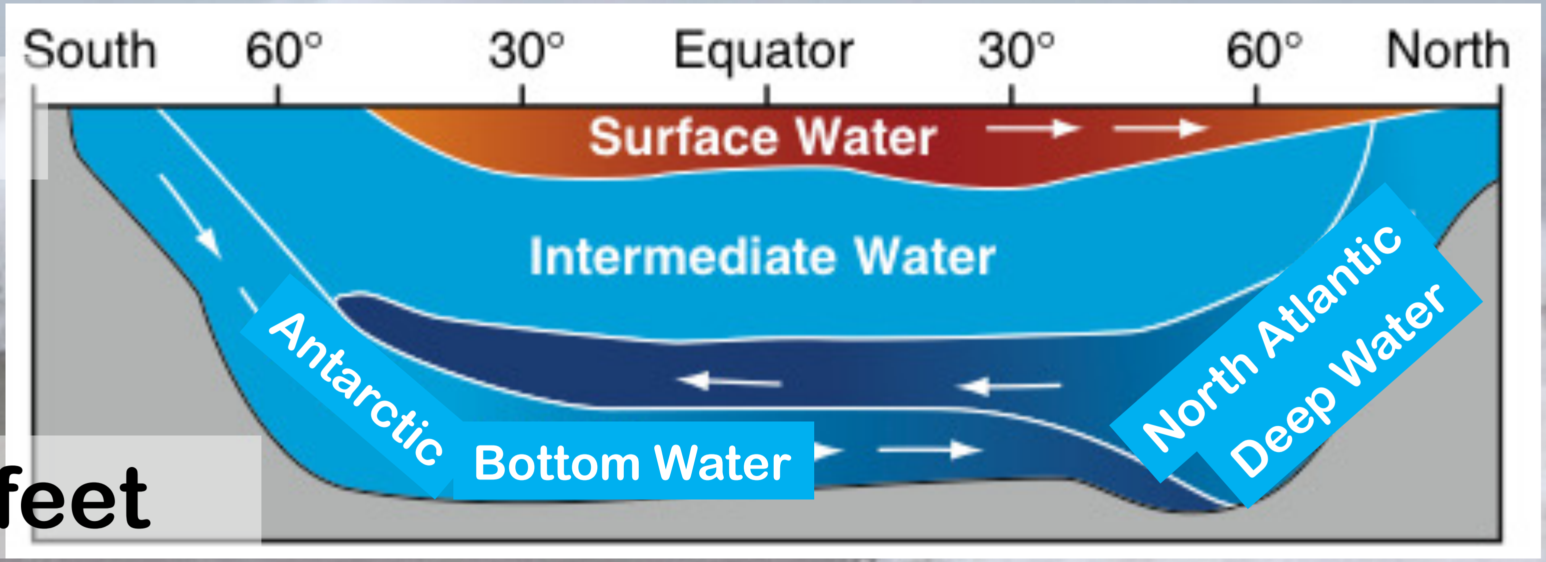
- Brightly colored equipment, fish, and corals at snorkel depths (10 – 20 feet)
- Red and orange go first, then yellow and green
- Below 50 feet, everything is progressively dimmer shades of blue

But the oceans are 13,000 feet deep!

really cold too!

Oceans Have Layers

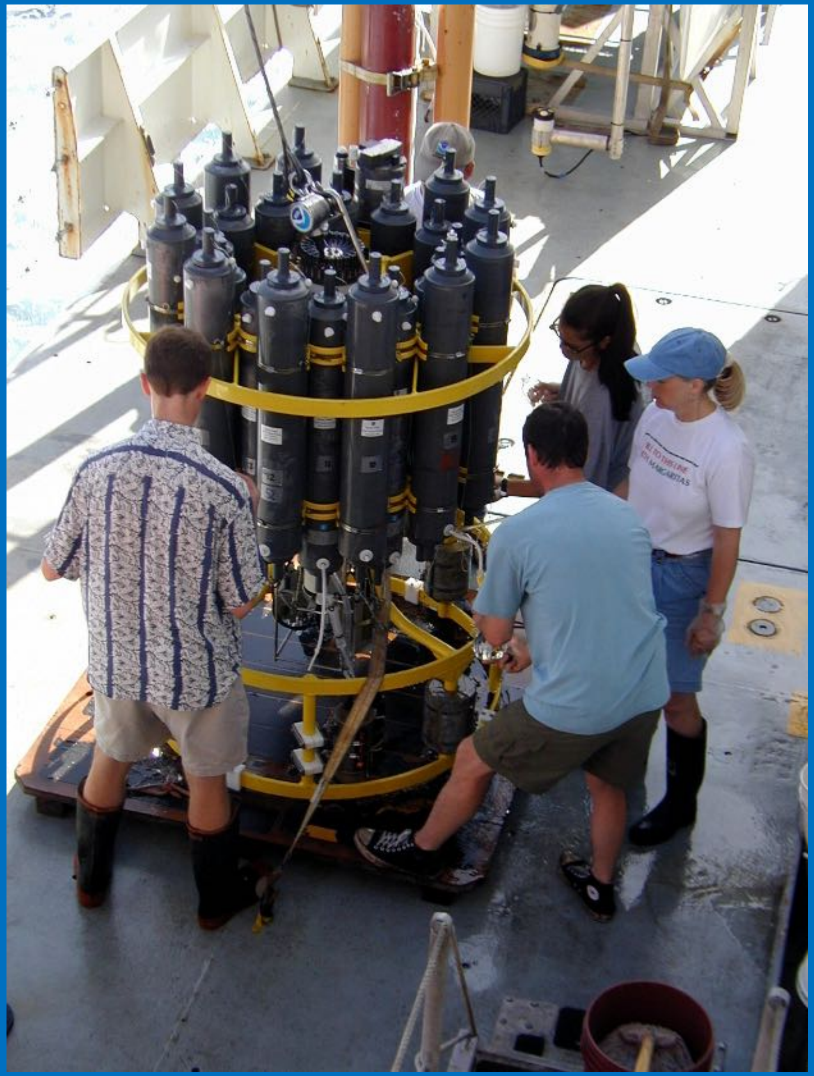
surface



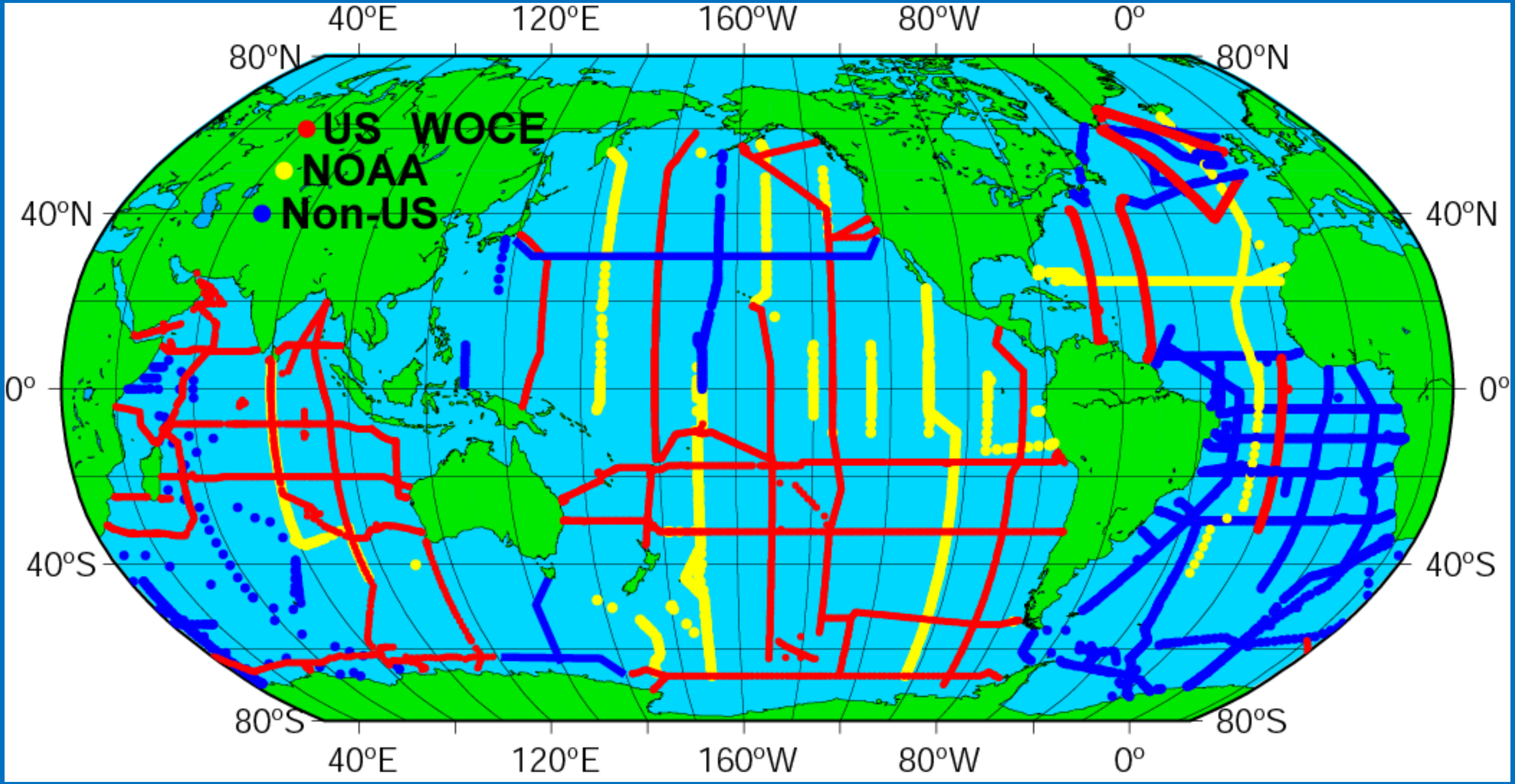
13,000 feet

- Warm **buoyant "raft"** floats at surface
- Cold deep water is only "formed" at high latitudes
- Very stable, **hard to mix, takes ~ 1000 years!**
- Icy cold, inky black, most of the ocean **doesn't know we're here yet!**

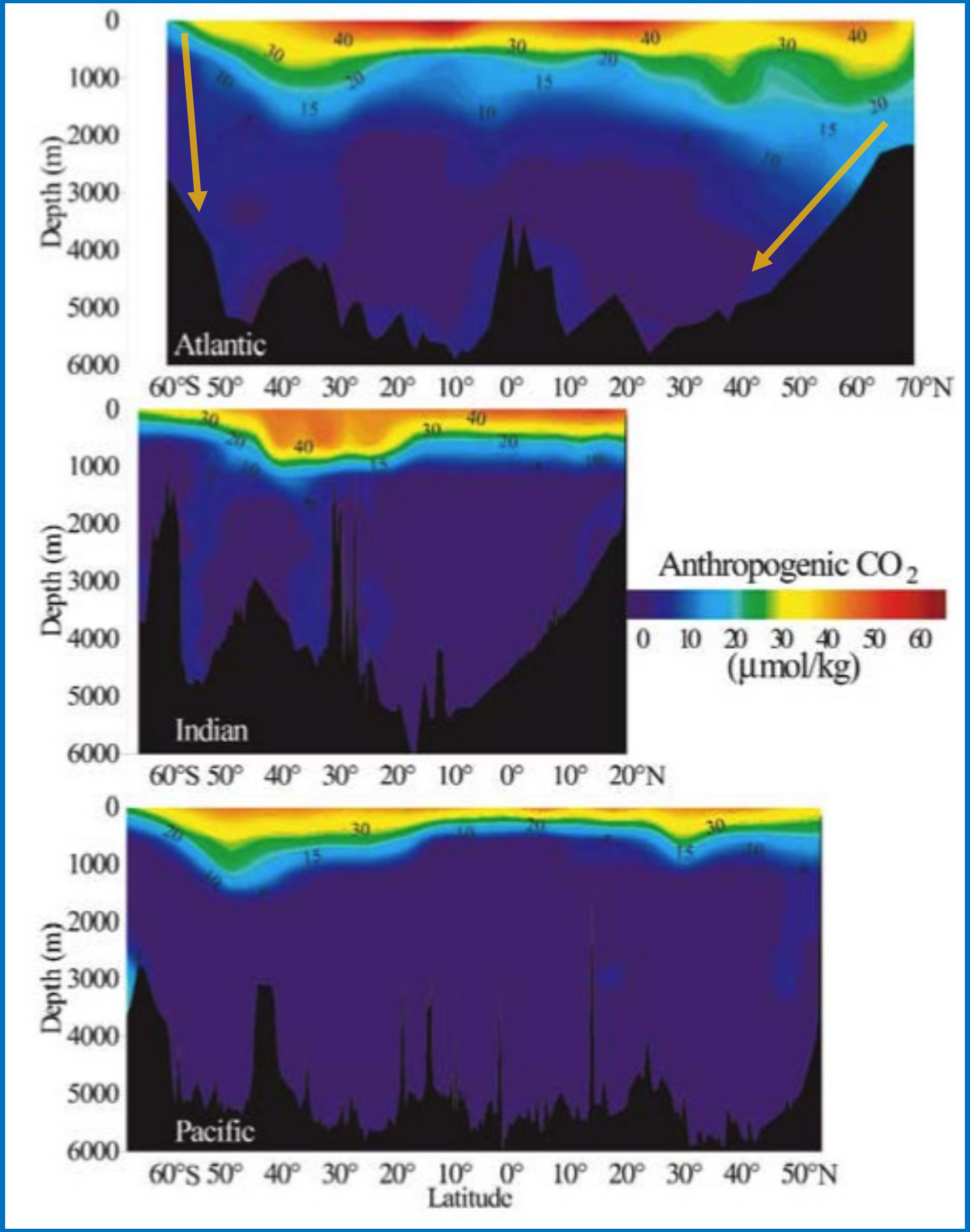
Observing the Deep Ocean



Observing the Deep Ocean



Global Ocean Survey Samples



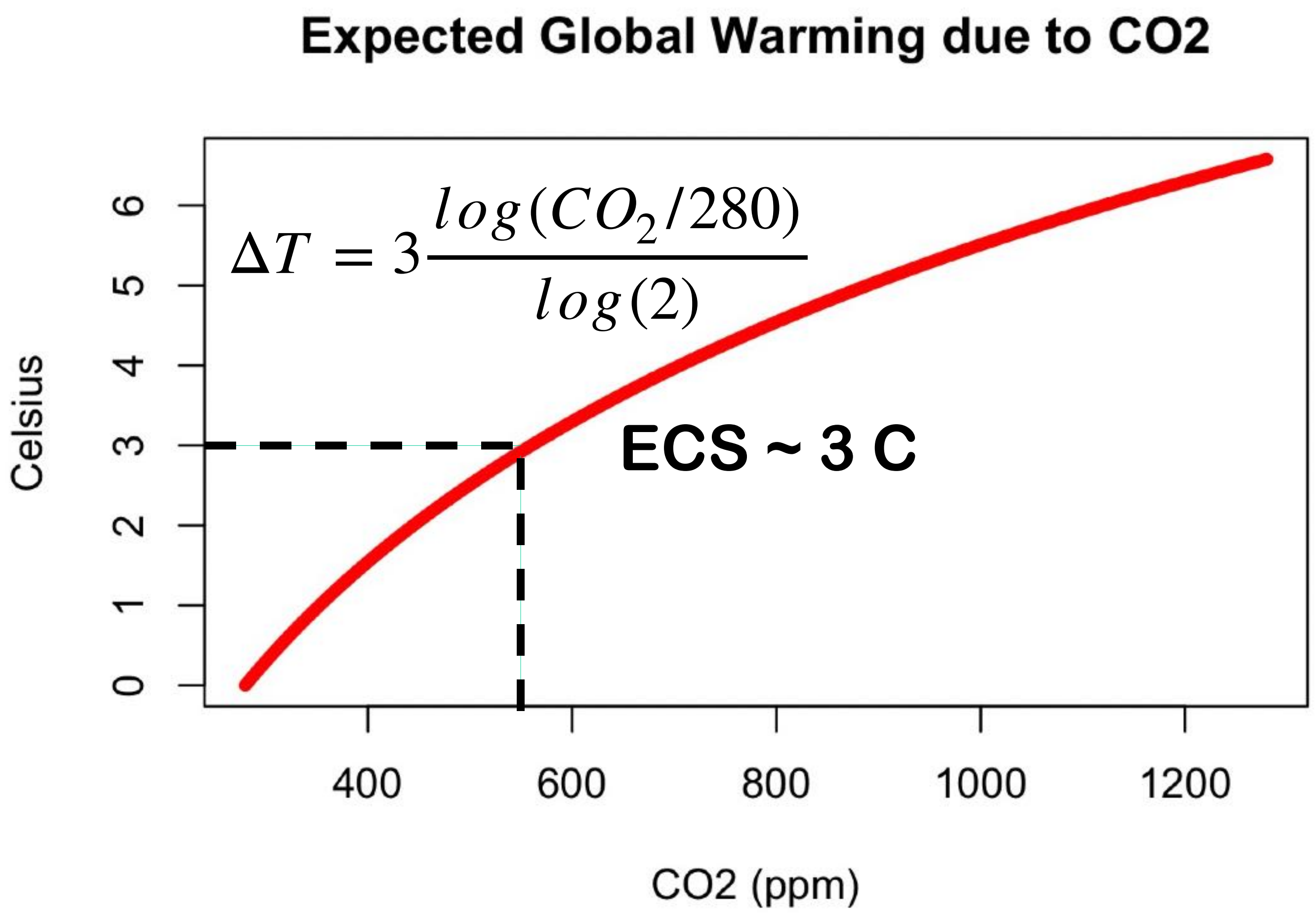
Dissolved Fossil CO_2

- **Millions of direct measurements of dissolved CO_2 in the oceans**
- **Fossil CO_2 remains trapped near the surface where warm water floats**
- ***Deep water doesn't know we're here yet!***

Climate Futures on the Back of an Envelope

Equilibrium Climate Sensitivity

- For 125 years, we've known that gases absorb radiation in proportion to the log of their concentration
- Tested in the lab, outdoors, from towers, balloons, aircraft, satellites



3° C of Warming Per Doubling of CO_2

Atmospheric CO_2 on the Back of an Envelope

Global fossil fuel emissions ~10 GtC/yr

~ 25% dissolves into oceans ~ 2.5 GtC/yr

~ 25% turns into land biomass ~ 2.5 GtC/yr

~ 50% remains in the air ~ 5 GtC/yr

5 GtC/yr in the air

~ 2.5 ppm CO_2 per year

Emissions

- **Global CO_2 emissions are about 10 GtC/yr**

- **One GtC means one Gigaton Carbon**
  = 1 billion tons of carbon = 10^9 tons of carbon
  = 10^{12} kg of carbon = 10^{15} g of carbon
- **One Gigaton (10^{12} tons) and one Petagram (10^{15} grams) are exactly the same thing!**
- **When carbon is burned (reacted w/ oxygen to make CO_2), 1 GtC + 2.7 GtC makes 3.7 GtCO2**

Where Has All the Carbon Gone?

- Into the **oceans**
  - **Solubility pump** (CO_2 very soluble in cold water, but rates are limited by slow physical mixing)
  - **Biological pump** (slow "rain" of organic debris)
- Into the **land**
  - **CO_2 Fertilization** (plants eat CO2 … is more better?)
  - **Nutrient fertilization** (N-deposition and fertilizers)
  - **Land-use change** (forest regrowth, fire suppression, woody encroachment … but what about Wal-Marts?)
  - **Response to changing climate** (e.g., Boreal warming)

Emissions -> Concentration

- Carbon sinks currently remove about half of CO_2 emissions
- The other half remains in the atmosphere for a REALLY LONG time
- So 10 GtC/yr of emissions is only 5 GtC of CO_2 increase
- Every GtC adds about 0.5 ppm of CO_2 concentration
- **So 10 GtC/yr of emissions adds about 2.5 ppm/yr of atmospheric CO_2**

Concentration -> Warming

- Equilibrium Climate Sensitivity is about 3 CELSIUS PER DOUBLING of CO_2
- Complicated. Not linear. Logarithmic!
- Before fossil fuels, CO_2 was about 280 ppm (~ yr 1800)

- WARMING = 3 C * log(CO_2/280) / log(2)

- EXAMPLE: How warm if CO_2 reaches 500 ppm ?
  - WARMING = 3 C * log(500_2/280) / log(2) = 2.5 C

Global Warming
on the Back of an E...

BUT CO_2 IS ALREADY 417 ppm!
SO HOW IS 1.5 STILL ALIVE?

To limit E...

... ΔT + 5.635)

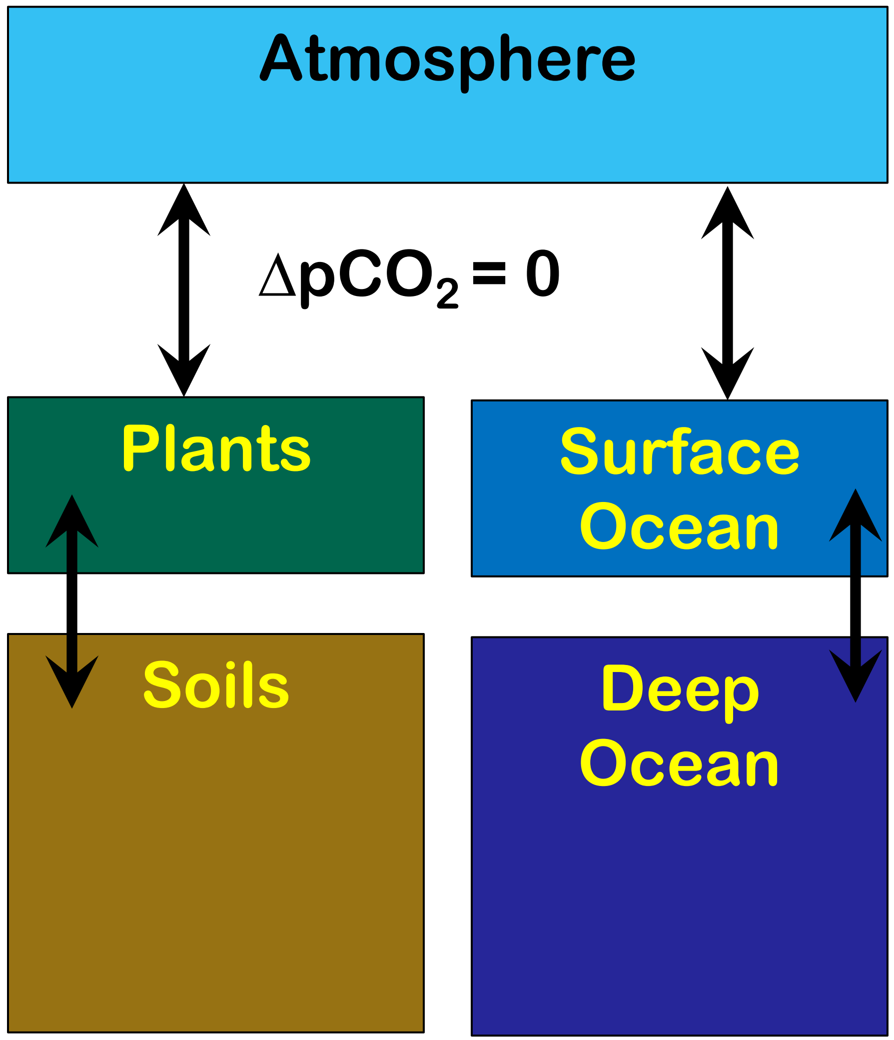
Limit warming to 3.0 °C; Limit CO2 to 560 ppm
Limit warming to 2.5 °C; Limit CO2 to 499 ppm
Limit warming to 2.0 °C; Limit CO2 to 445 ppm
Limit warming to 1.5 °C; Limit CO2 to 396 ppm (oops)

Sink Saturation

- Land – very vulnerable, very uncertain!
  - Only CO_2 fertilization has “legs”
  - N-deposition and Regrowth are transient
  - Boreal warming may switch to a huge source!
- Ocean – slow & safe for near-term, scary for the long term
  - Limited by rate of physical mixing into deep ocean against buoyancy
  - As surface water warms, mixing will slow
  - Thousands of years to reach equilibrium!
  - Acidification chemistry limits total uptake

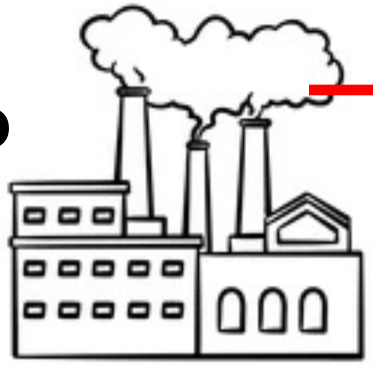
Simple Conceptual Model

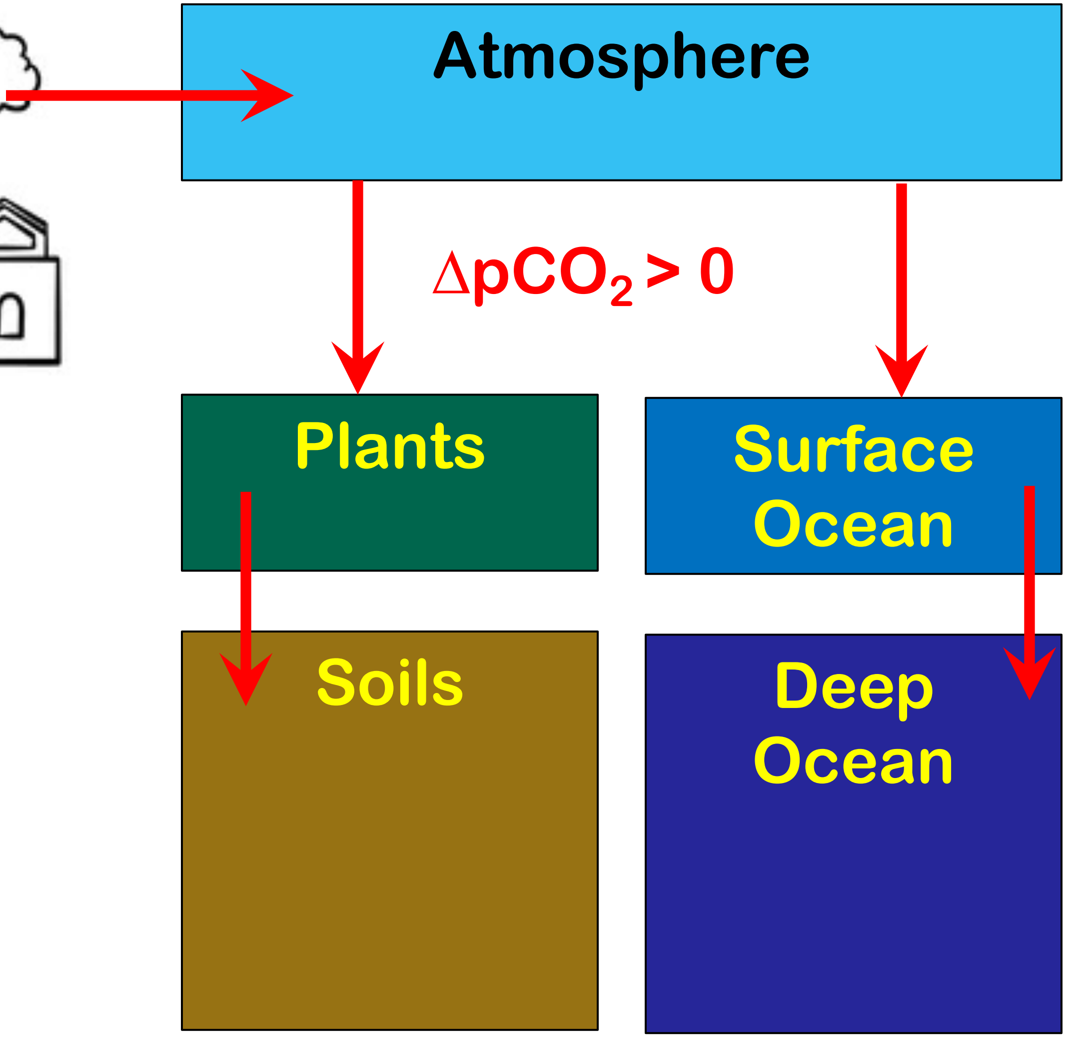
- Preindustrial equilibrium: Historically, there were no carbon sinks



Simple Conceptual Model

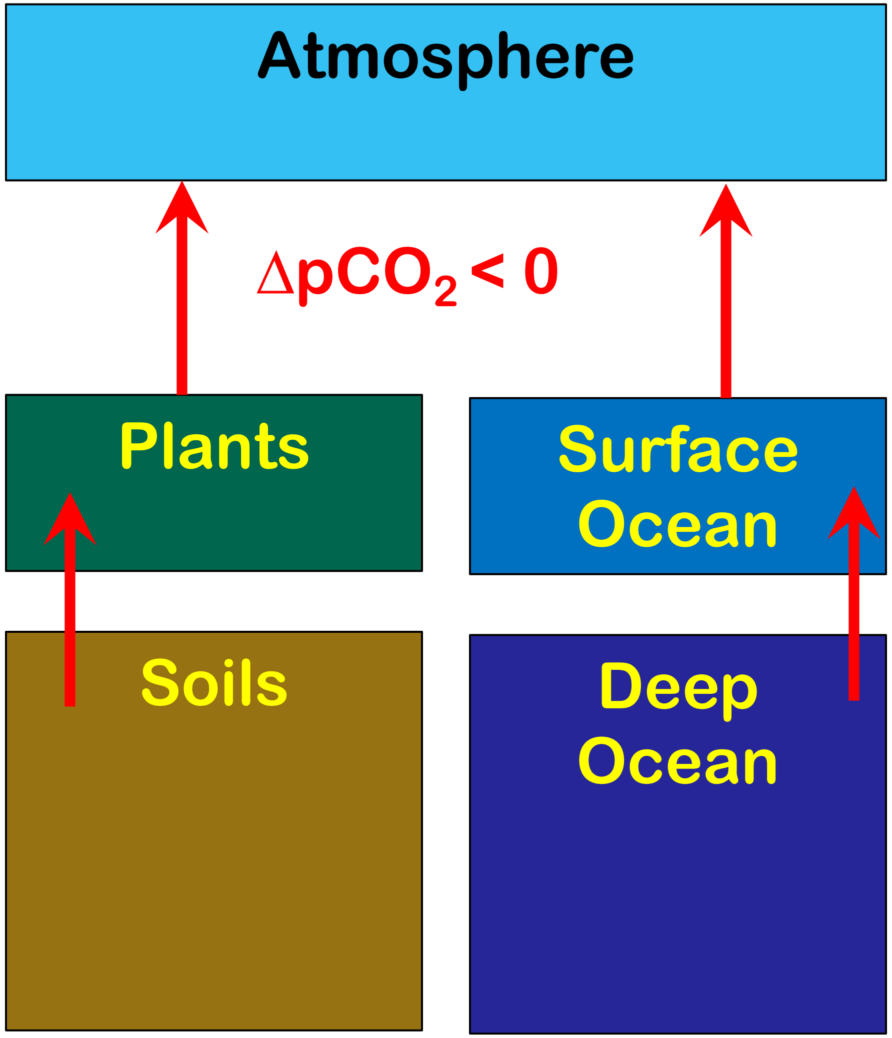
- Preindustrial equilibrium: Historically, there were no carbon sinks
- As atmospheric CO2 increased, carbon flowed into the surface ocean and land ecosystems

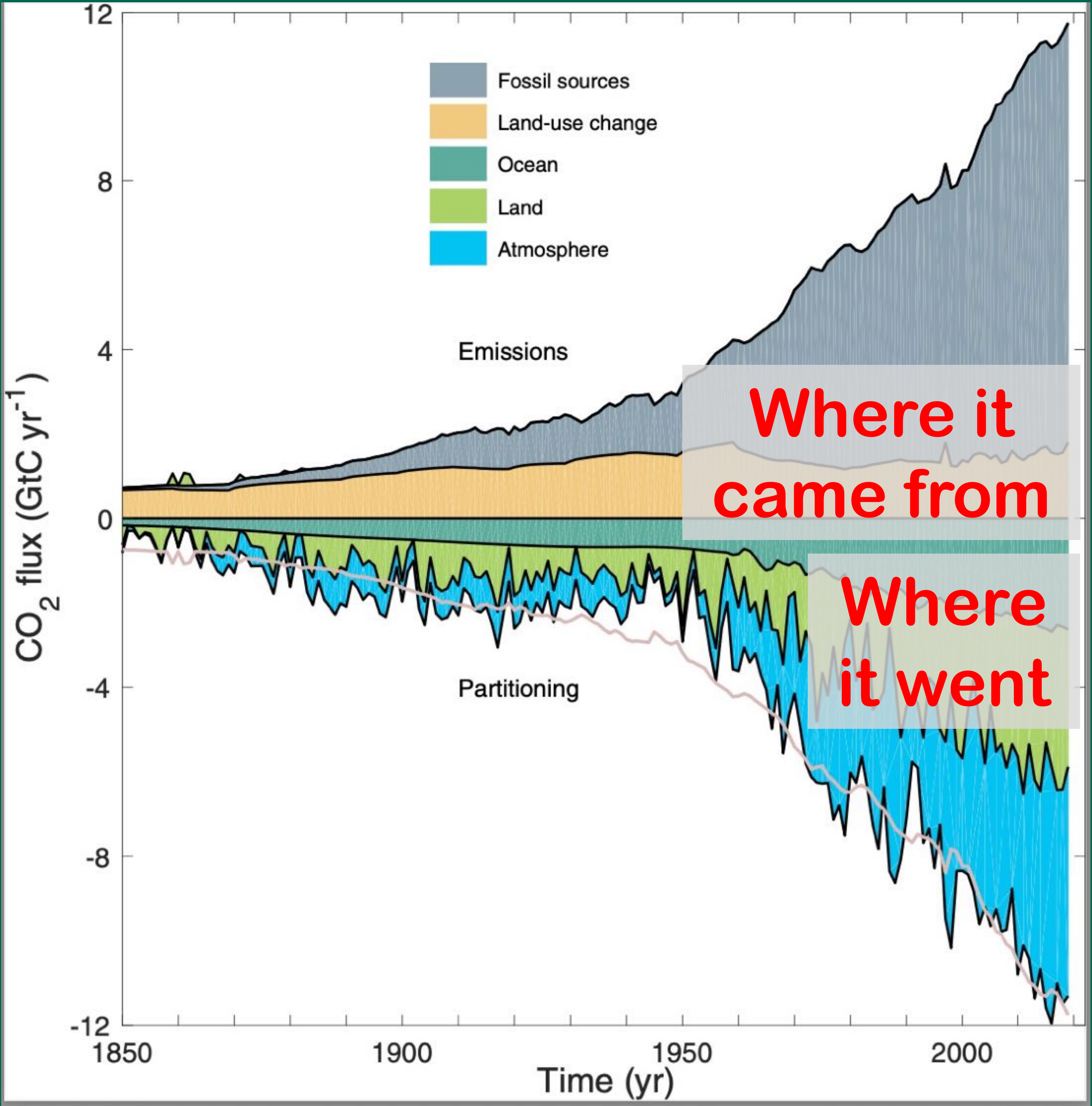




Simple Conceptual Model

- Preindustrial equilibrium: Historically, there were no carbon sinks
- As atmospheric CO2 increased, carbon flowed into the surface ocean and land ecosystems
- As emissions slow and cease, ΔpCO_2 will fall
- If/when emissions reverse, so will the sinks





Historical Sources & Sinks of CO_2

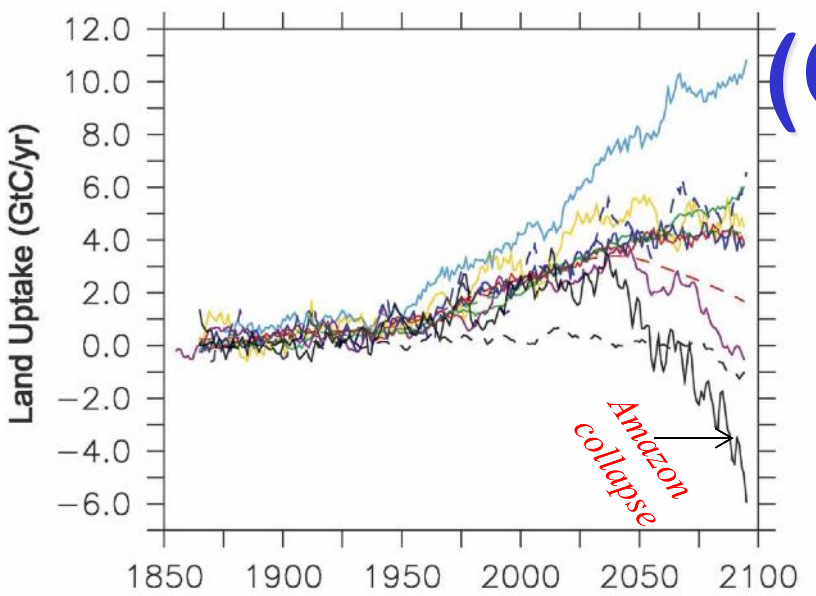
Sources:

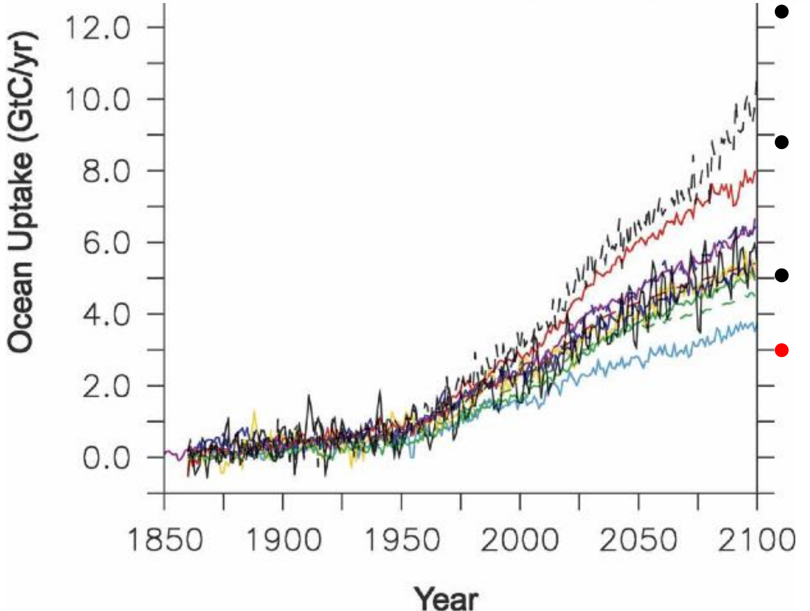
- Fossil fuel combustion ~ 90%
- Deforestation ~ 10%

Sinks:

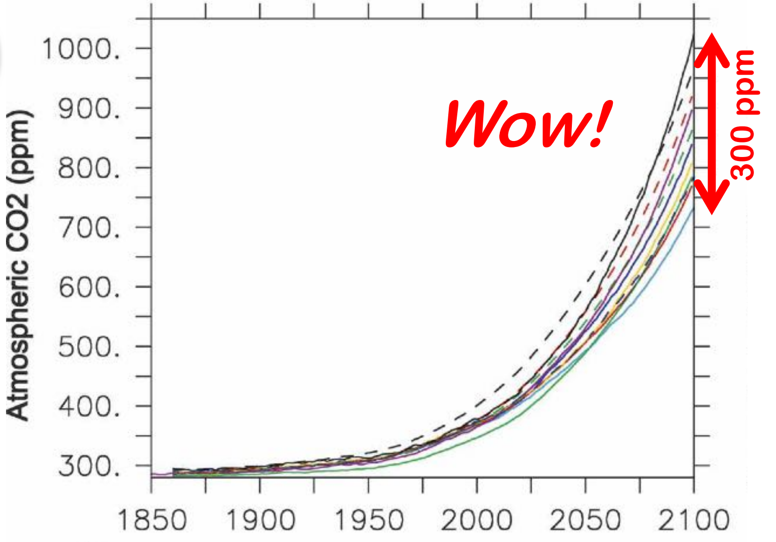
- Atmosphere ~ 50%
- Oceans ~ 25%
- Land ~ 25% (varies!)

Coupled Carbon Cycle Climate Model Intercomaprison Project (C^4MIP)





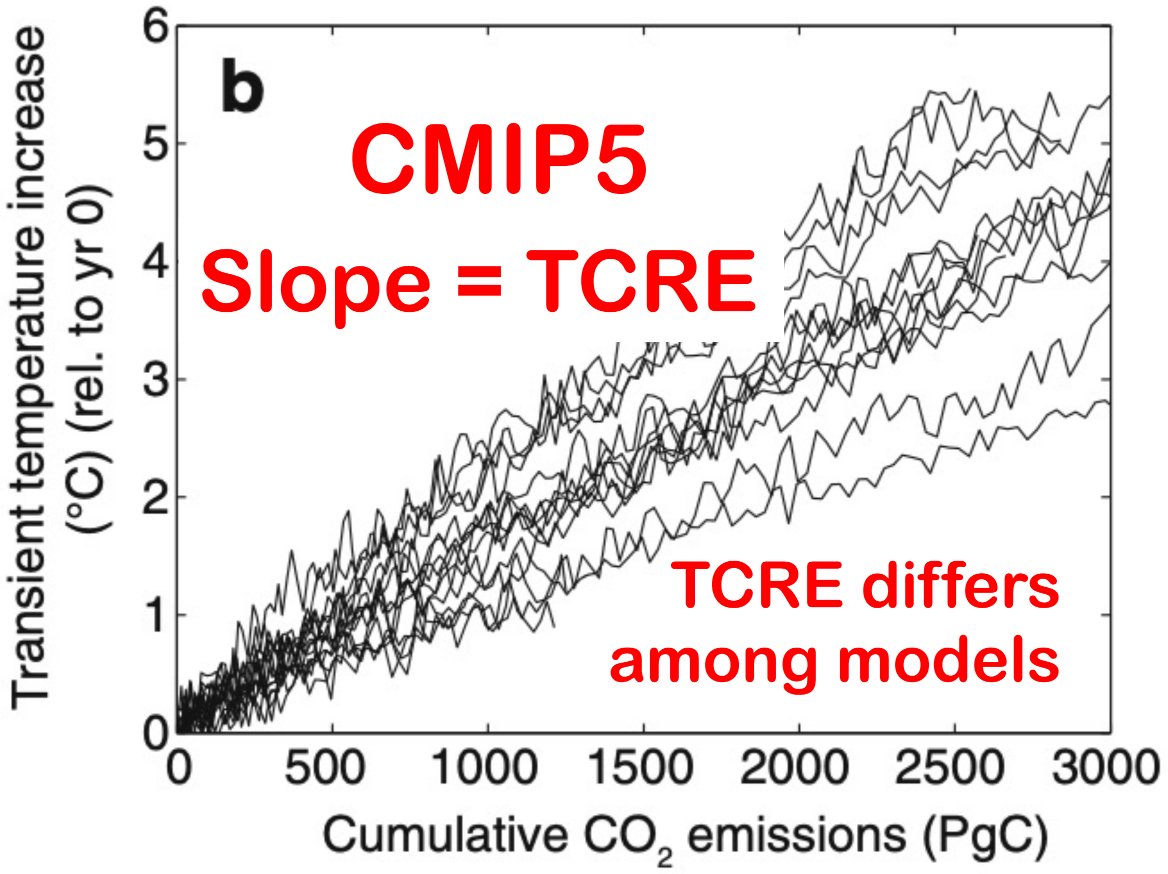
11 different climate models also including land and ocean carbon

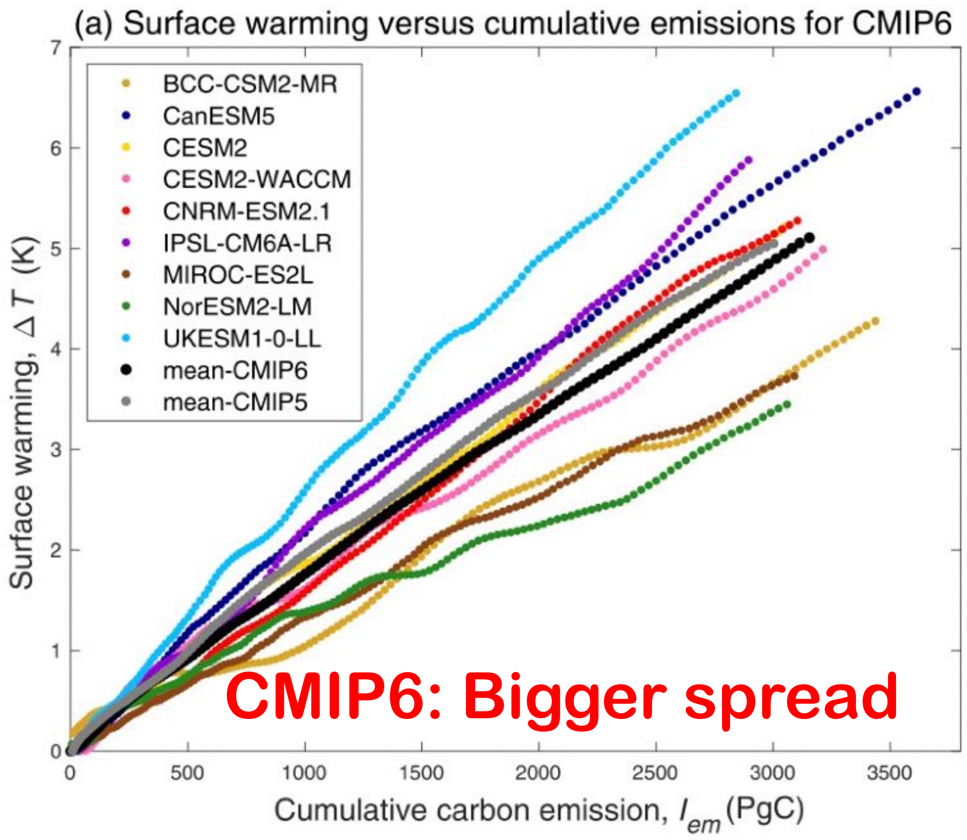


- All run from 1850-2100 forced by identical fossil fuel emissions (IPCC SRES scenario A2)
- Huge differences in behavior of land and ocean carbon cycles!
- Some tradeoffs between land and ocean
- Identical emissions produce 300 ppm difference in CO_2 by 2100 due to differences in carbon cycle behavior!

Friedlingstein et al (2006)

Emergence of TCRE





Warming is linear with cumulative emissions across many models with many different sensitivities!

Transient Climate Response to Emissions

"Definition"

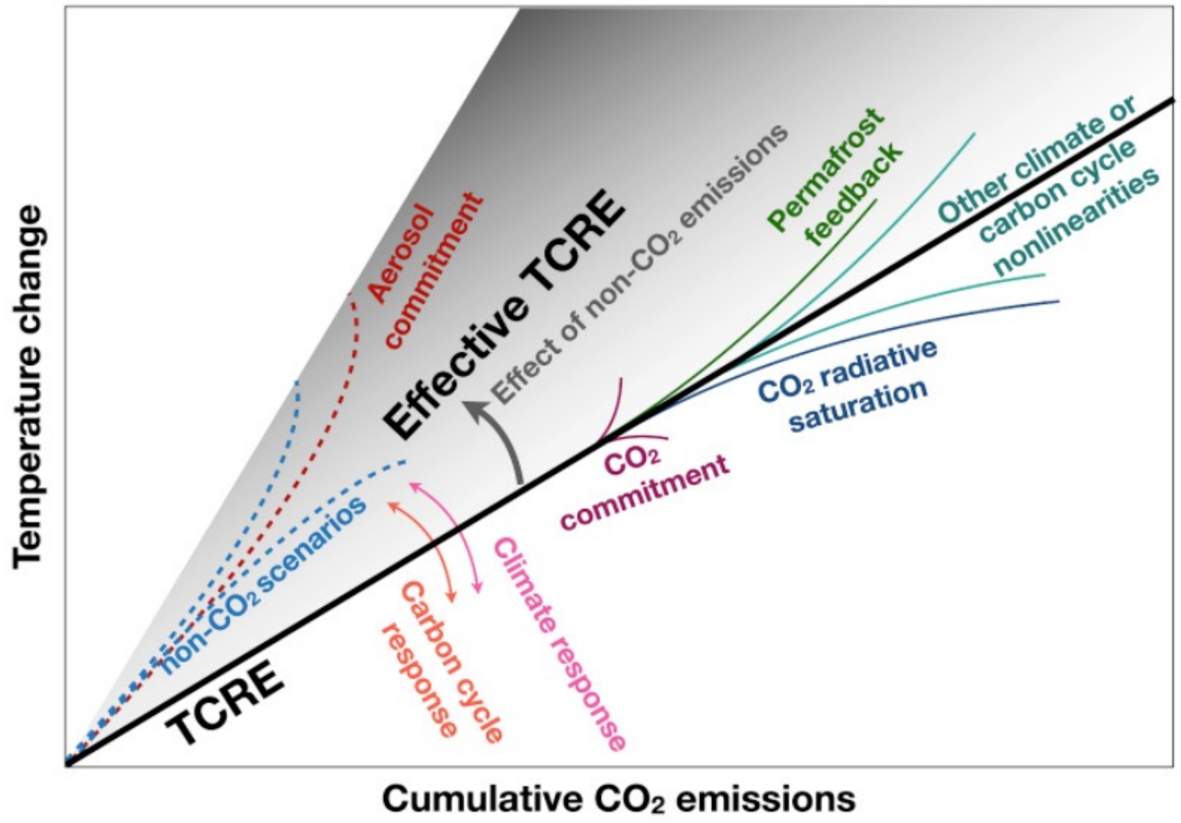
warming

$$\Lambda = \frac{\Delta T}{E} = \frac{\Delta T}{\Delta C_a} \times \frac{\Delta C_a}{E}$$

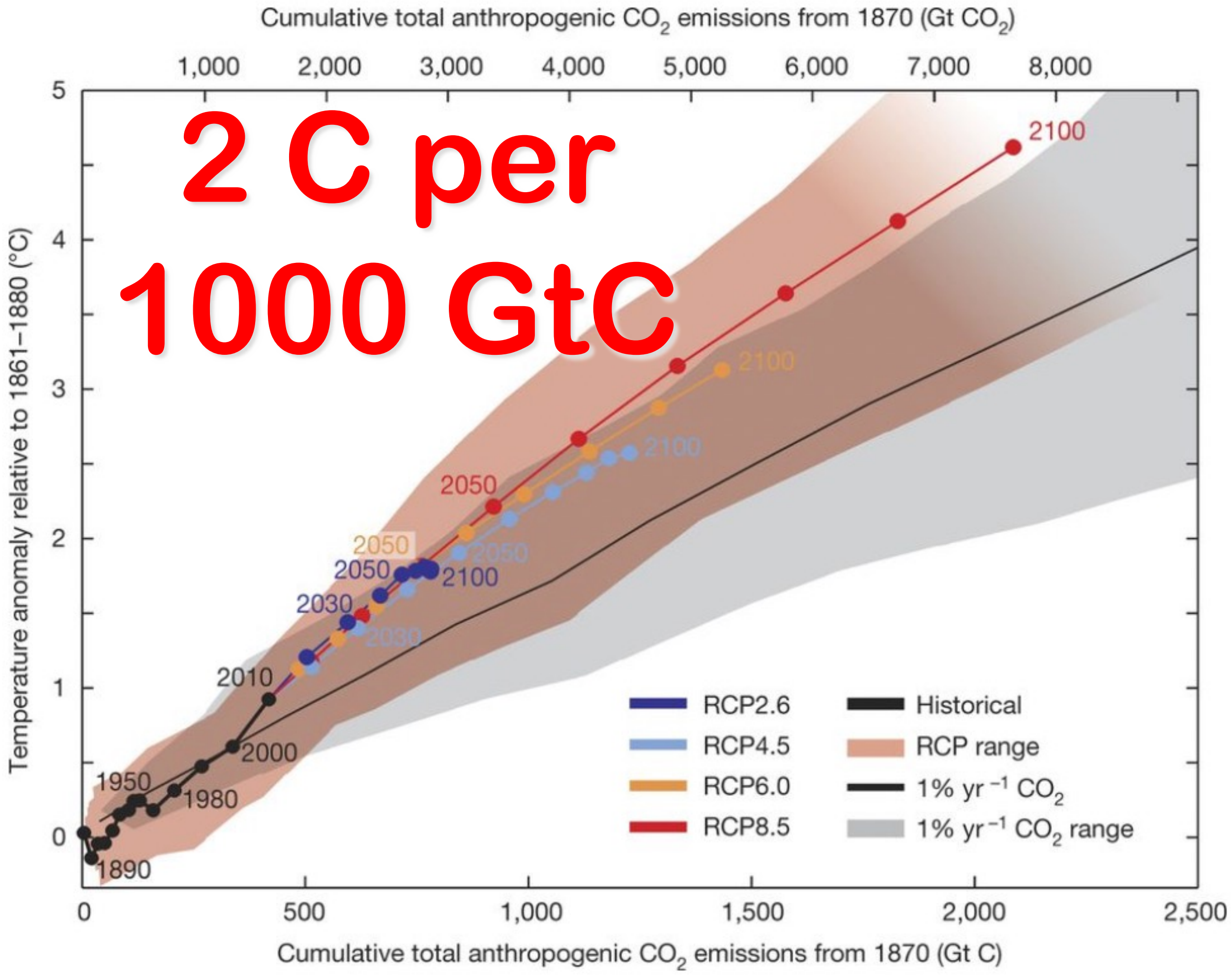
TCRE

cumulative emissions

CO_2 increment



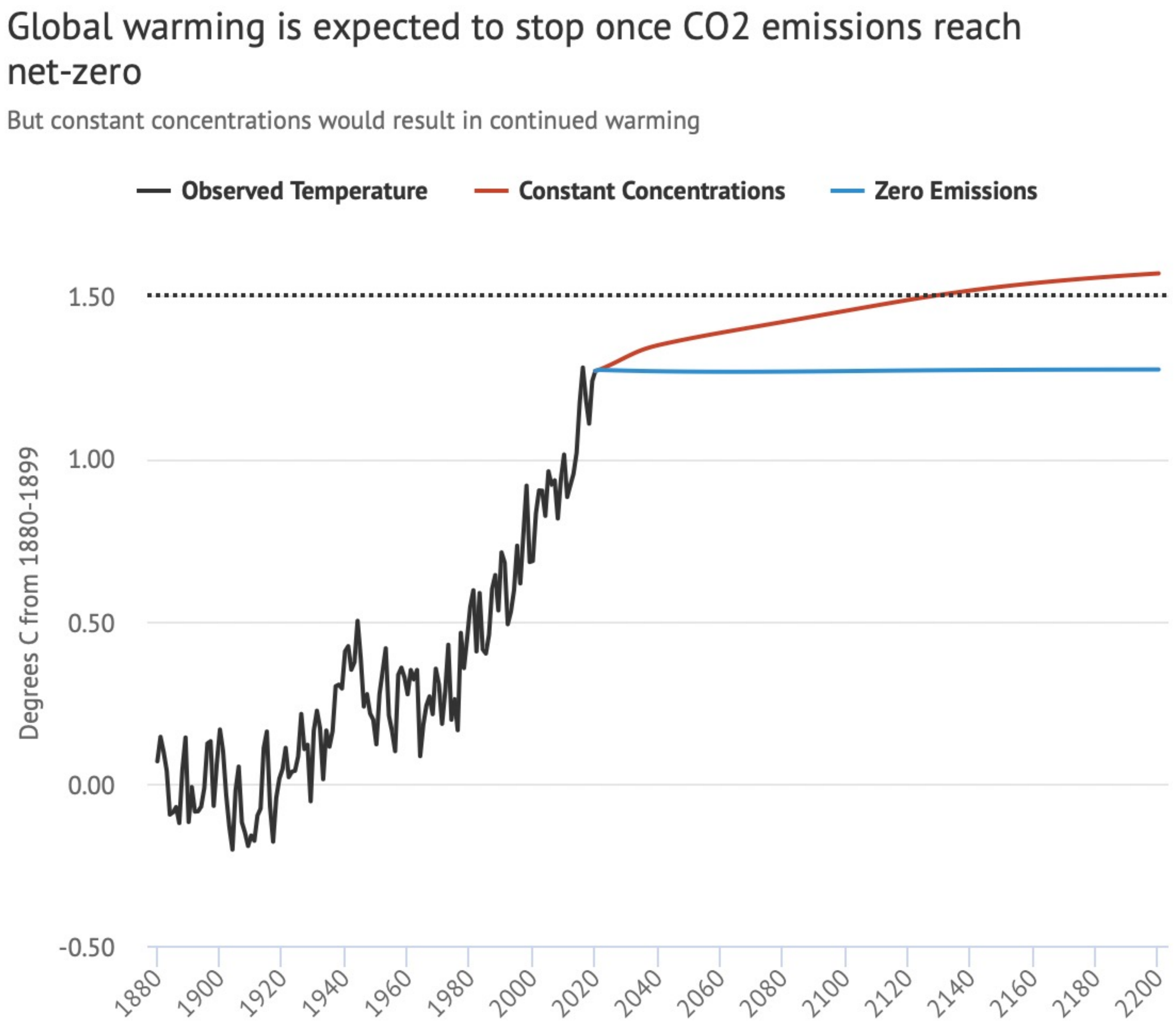
TCRE Spans Scenarios



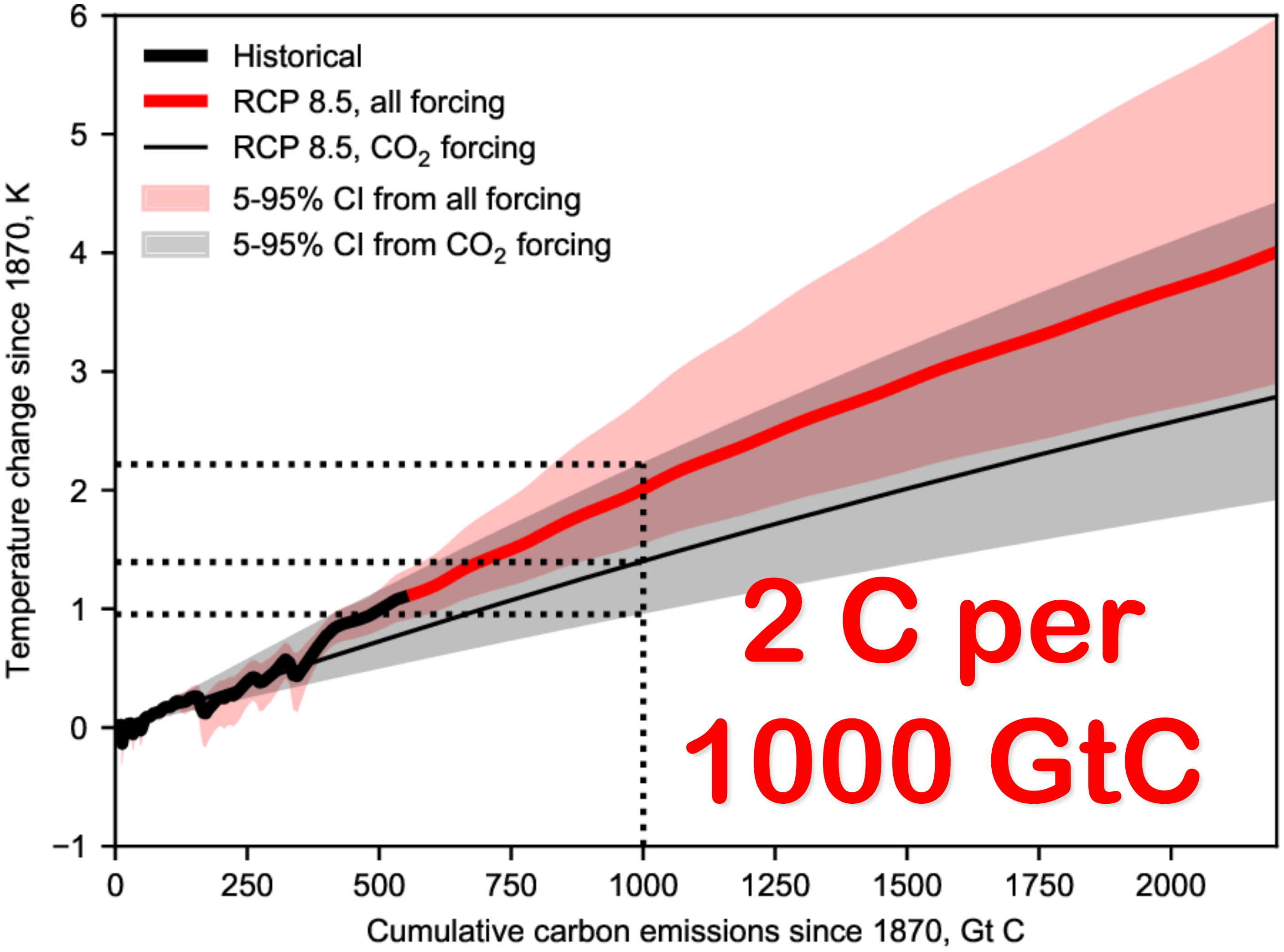
- Fits historical data & scenarios from RCP2.6 all the way up to RCP8.5!
- **SIMPLE RECIPE:**
  - Sum all historical emissions (in GtC not $GtCO_2$)
  - Warming = 2 C per 1000 GtC

“Zero Emission Commitment” ZEC

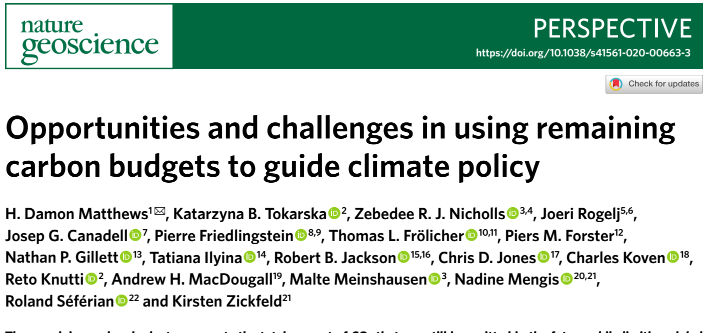
- **Intercomparison of ESMs forced with zero emissions ZEC-MIP**
- **NO WARMING “IN THE PIPELINE”**



Use TCRE to Define an “Allowable Emissions Budget”



- Cumulative emissions to date are about 600 GtC
- If TCRE = 2C / 1000 GtC, there are 400 GtC remaining emissions before we hit 2 C
- Only about 100 GtC can still be emitted to limit warming to 1.5 C


nature geoscience

PERSPECTIVE

https://doi.org/10.1038/s41561-020-00663-3

Check for updates

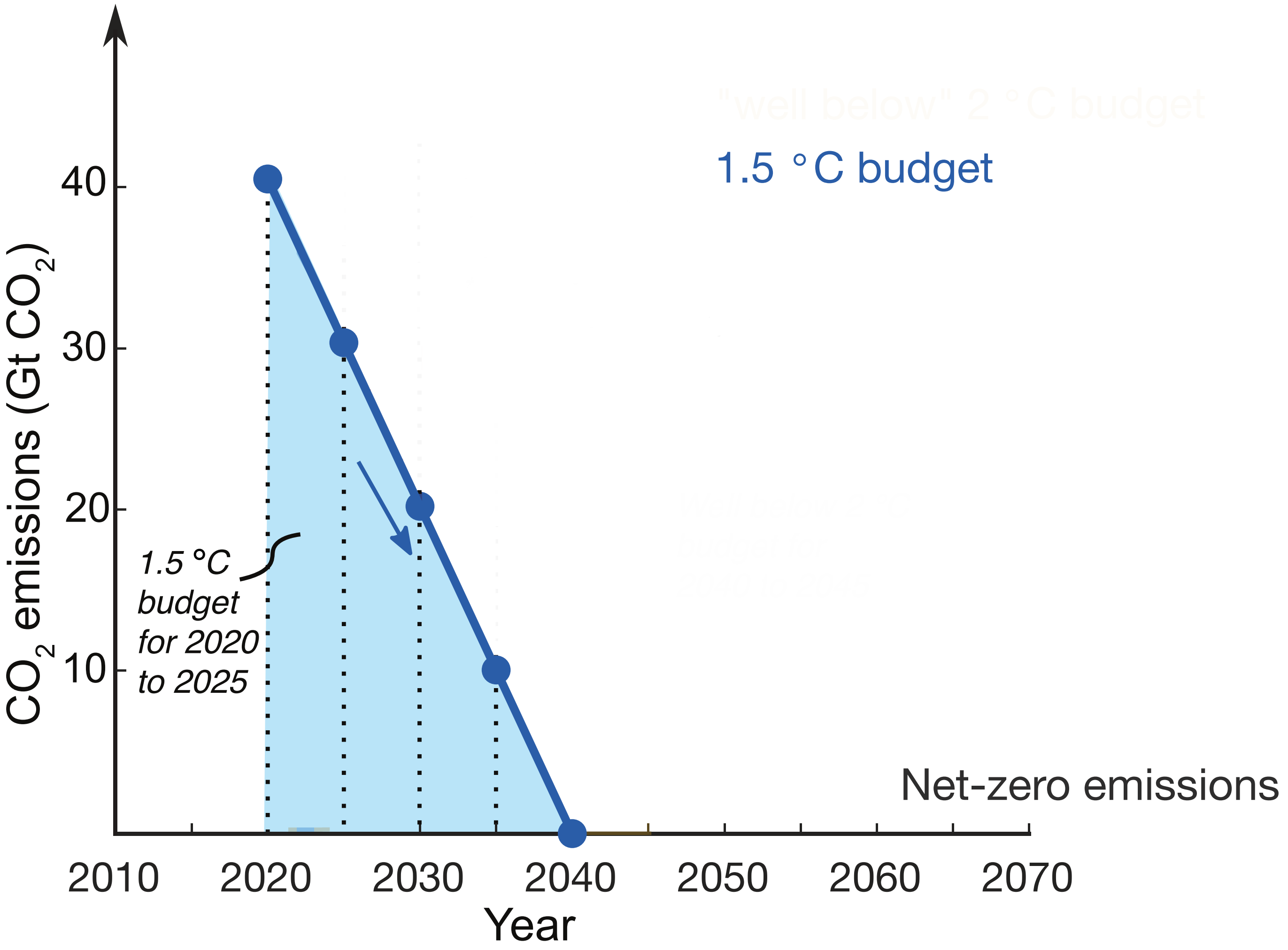
Opportunities and challenges in using remaining carbon budgets to guide climate policy

H. Damon Matthews[1], Katarzyna B. Tokarska[2], Zebedee R. J. Nicholls[3,4], Joeri Rogelj[5,6], Josep G. Canadell[7], Pierre Friedlingstein[8,9], Thomas L. Frölicher[10,11], Piers M. Forster[12], Nathan P. Gillett[13], Tatiana Ilyina[14], Robert B. Jackson[15,16], Chris D. Jones[17], Charles Koven[18], Reto Knutti[2], Andrew H. MacDougall[19], Malte Meinshausen[3], Nadine Mengis[20,21], Roland Séférian[22] and Kirsten Zickfeld[21]

An illustrative example of setting

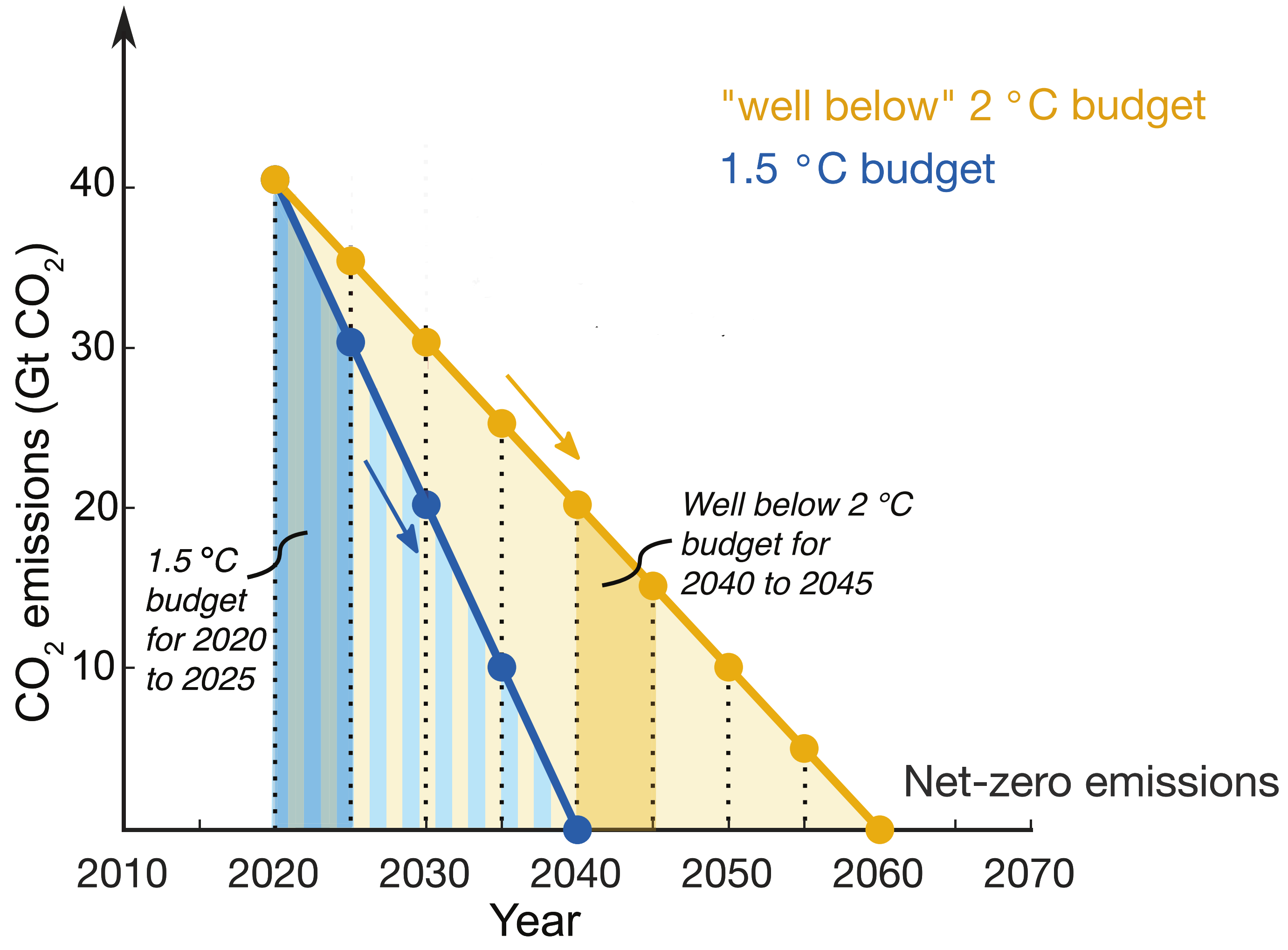
net-zero emission targets

within a given carbon budget



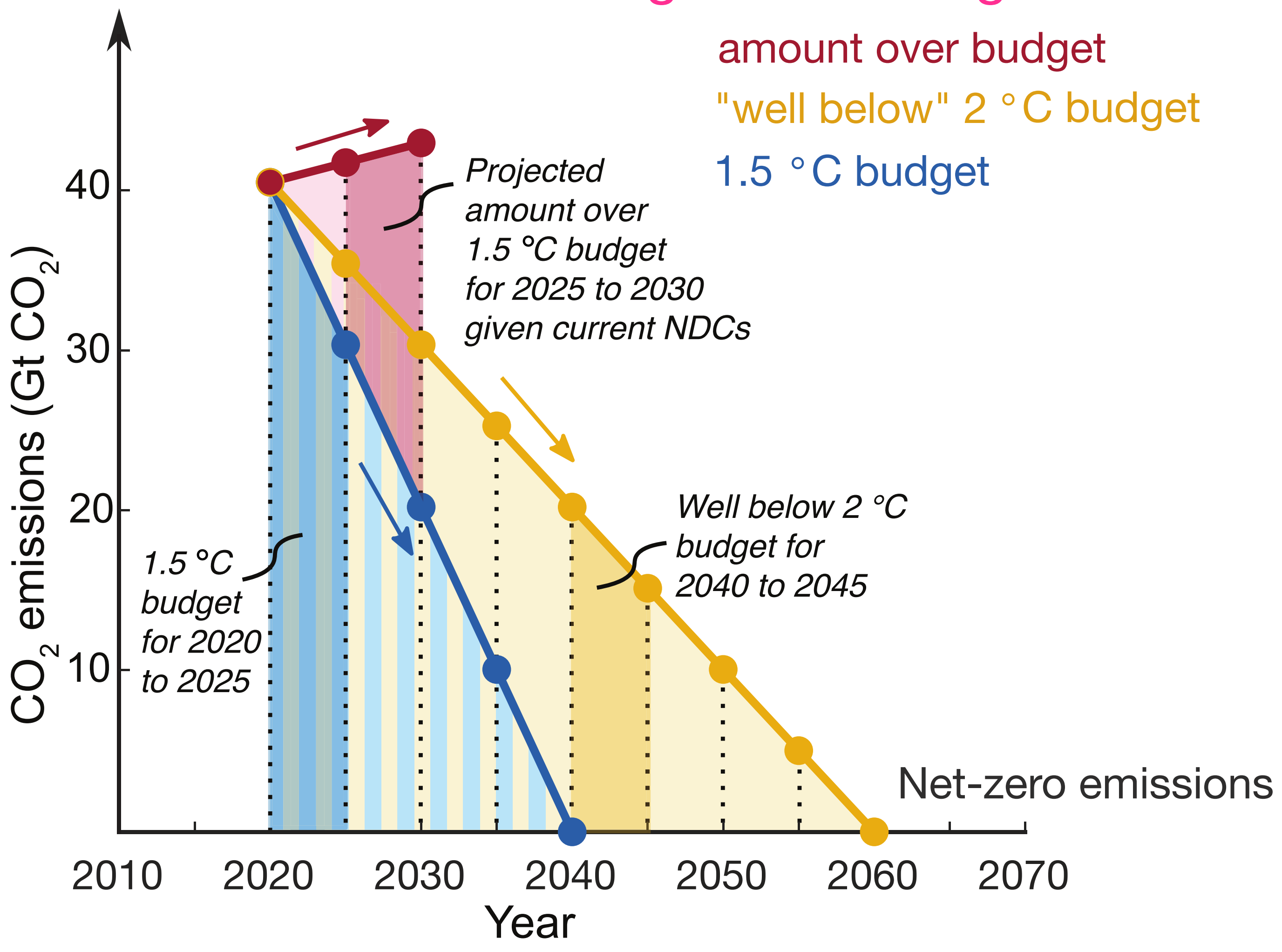
Matthews et al. 2020 Nat Geosci.

An illustrative example of setting **net-zero emission targets** within a given carbon budget



Matthews et al. 2020 Nat Geosci.

- Current **NDC pledges are insufficient** to meet the Paris Agreement long-term temperature stabilization goal



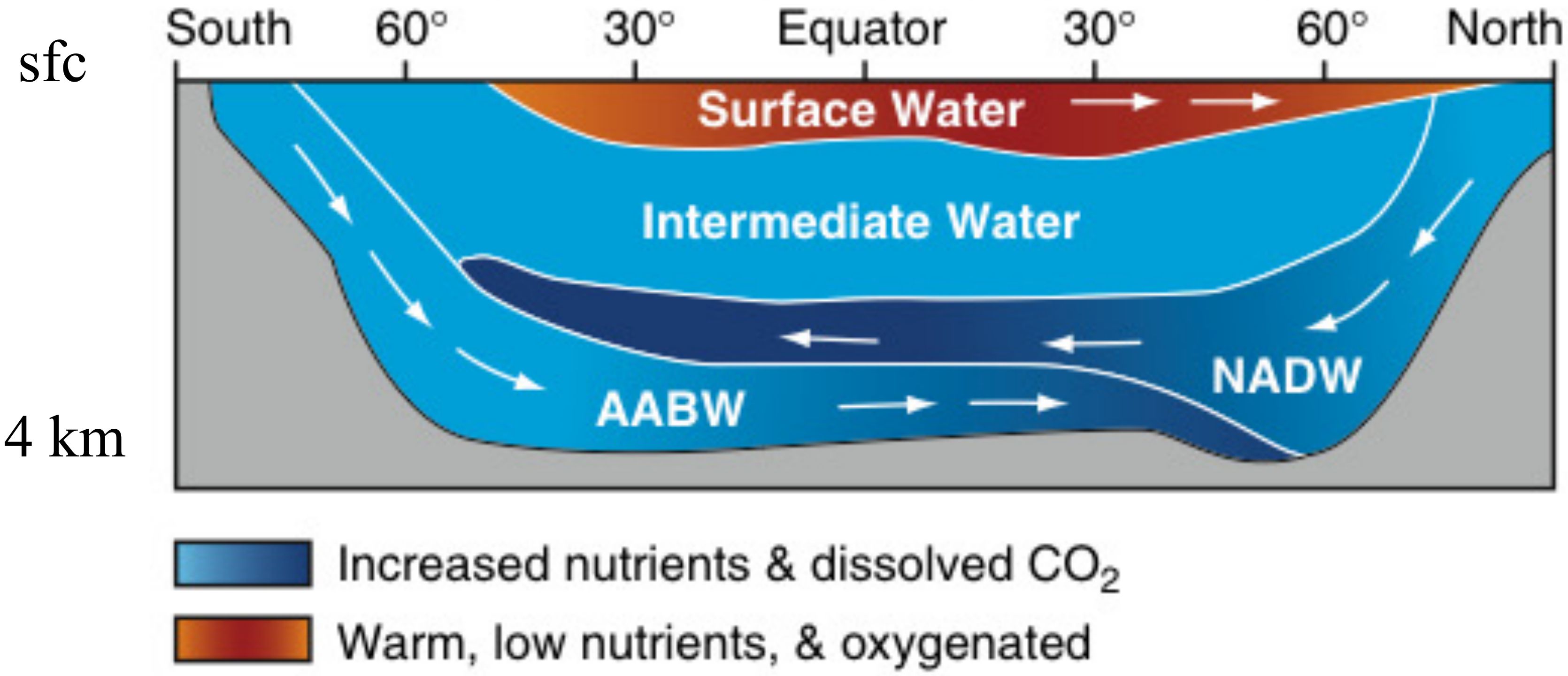
An illustrative example of setting **net-zero emission targets** within a given carbon budget

Stop setting stuff on fire

1. Every kg of carbon burned anywhere anytime adds an equal amount of global warming
2. When emissions stop, warming will stop (no warming in the pipeline!)
3. To stop warming, we must stop burning carbon

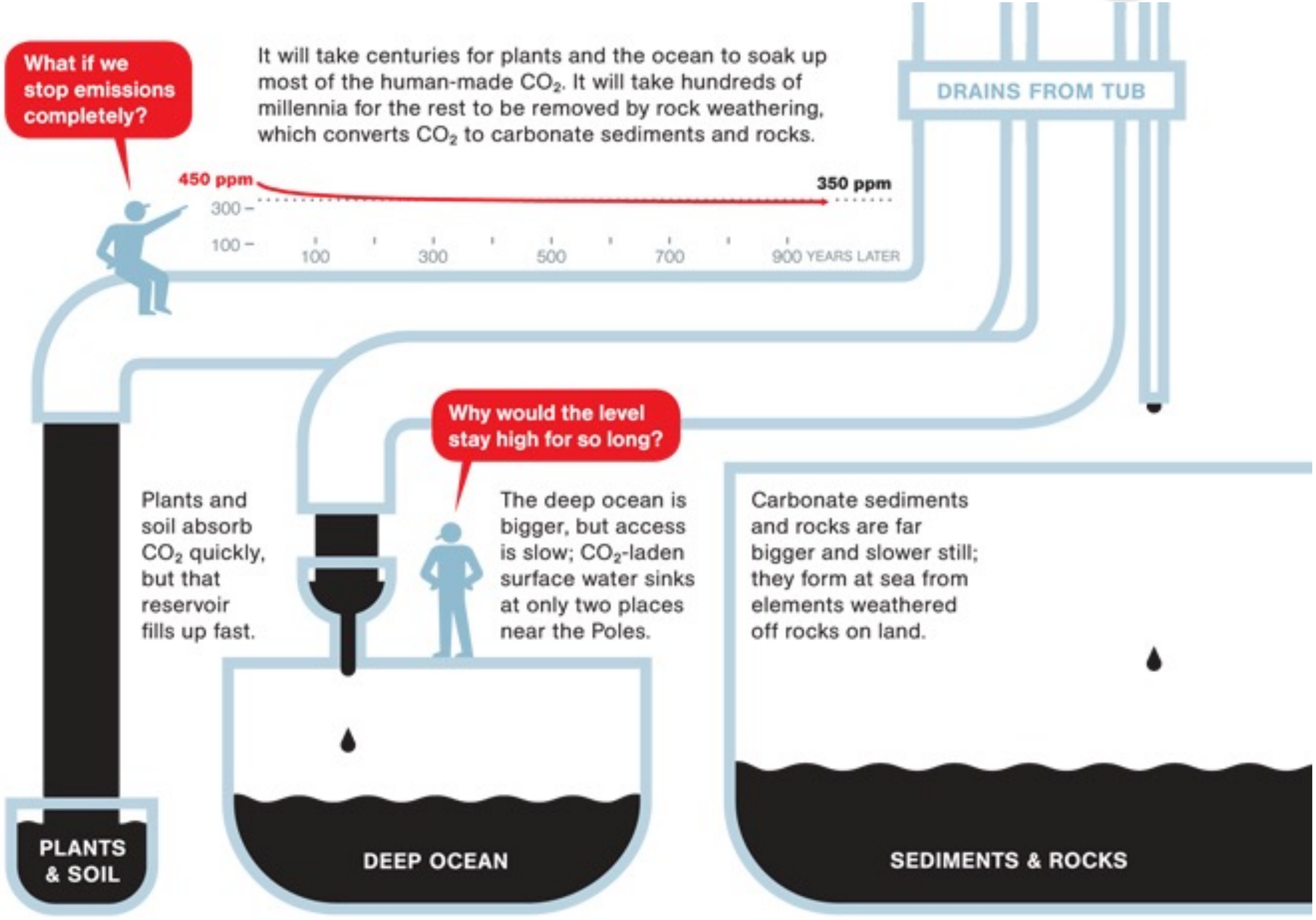
The
Long
Tail

Vertical Structure of the Oceans

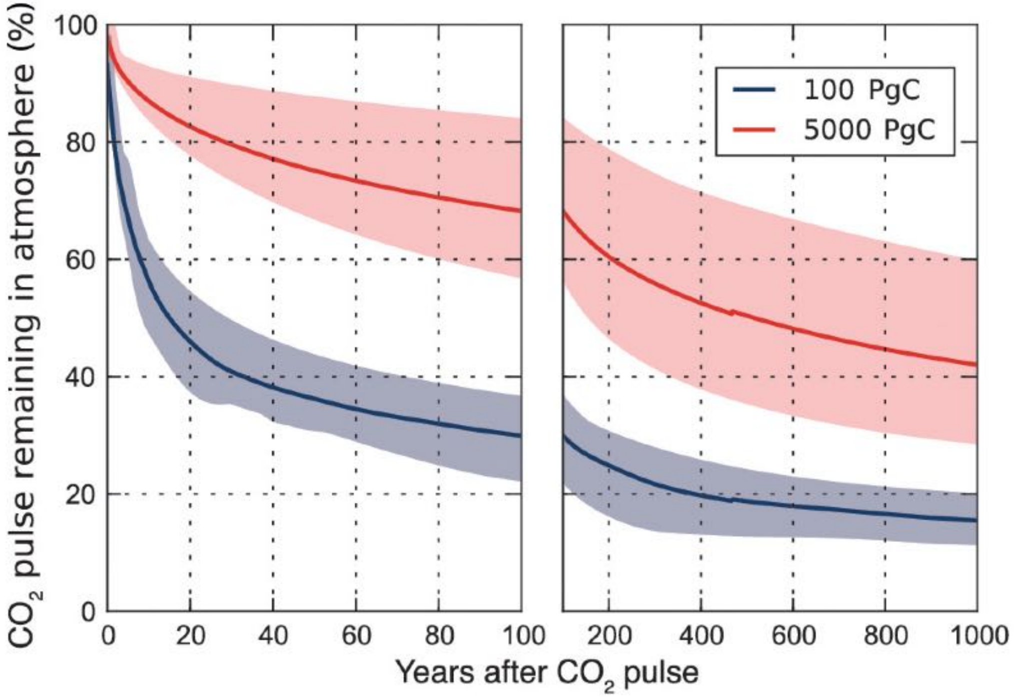


- Warm buoyant "raft" floats at surface
- Cold deep water is only "formed" at high latitudes
- Very stable, hard to mix, takes ~ 1000 years!
- Icy cold, inky black, most of the ocean doesn't know we're here yet!

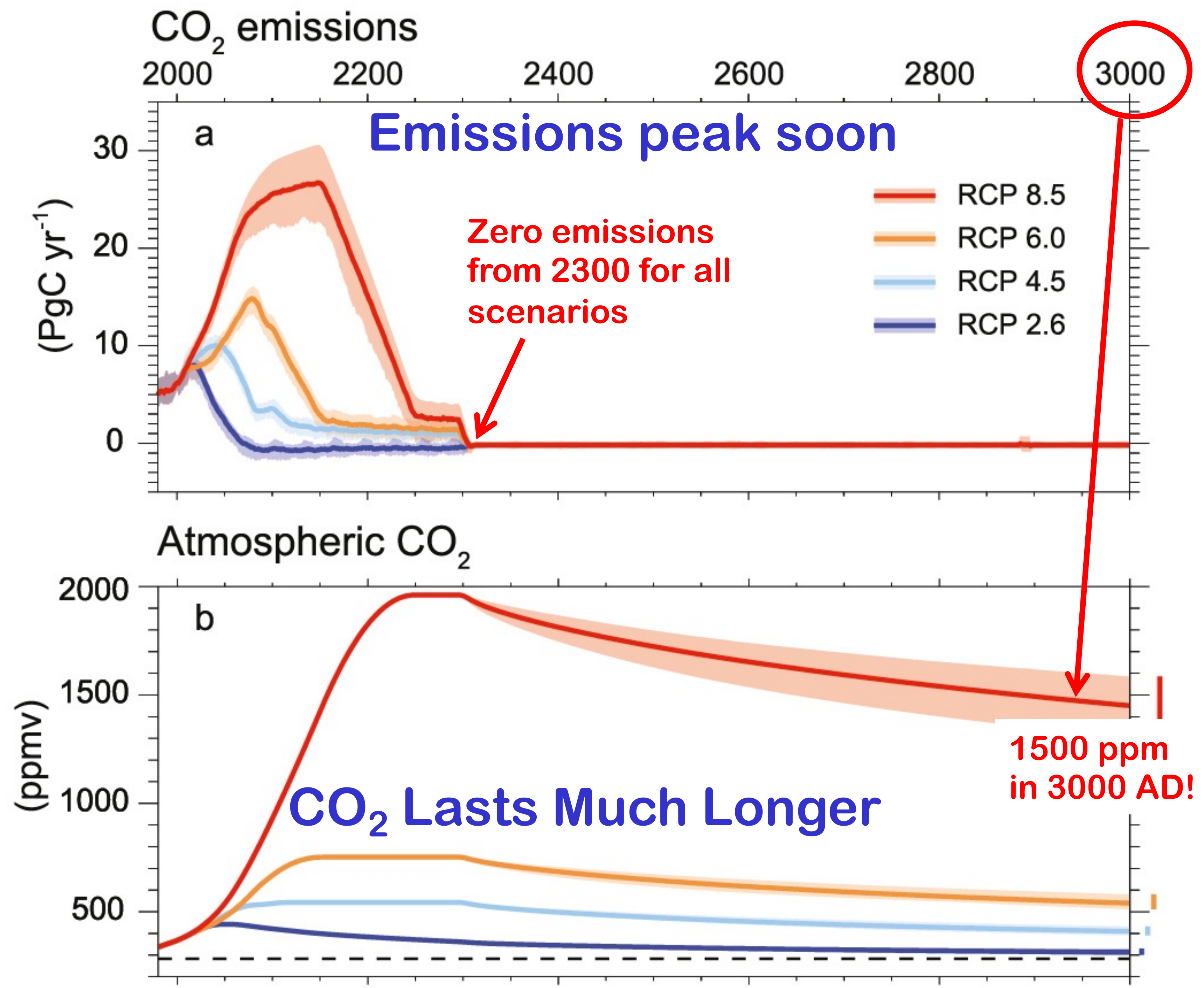
Bathtub Drainage



The Long Tail

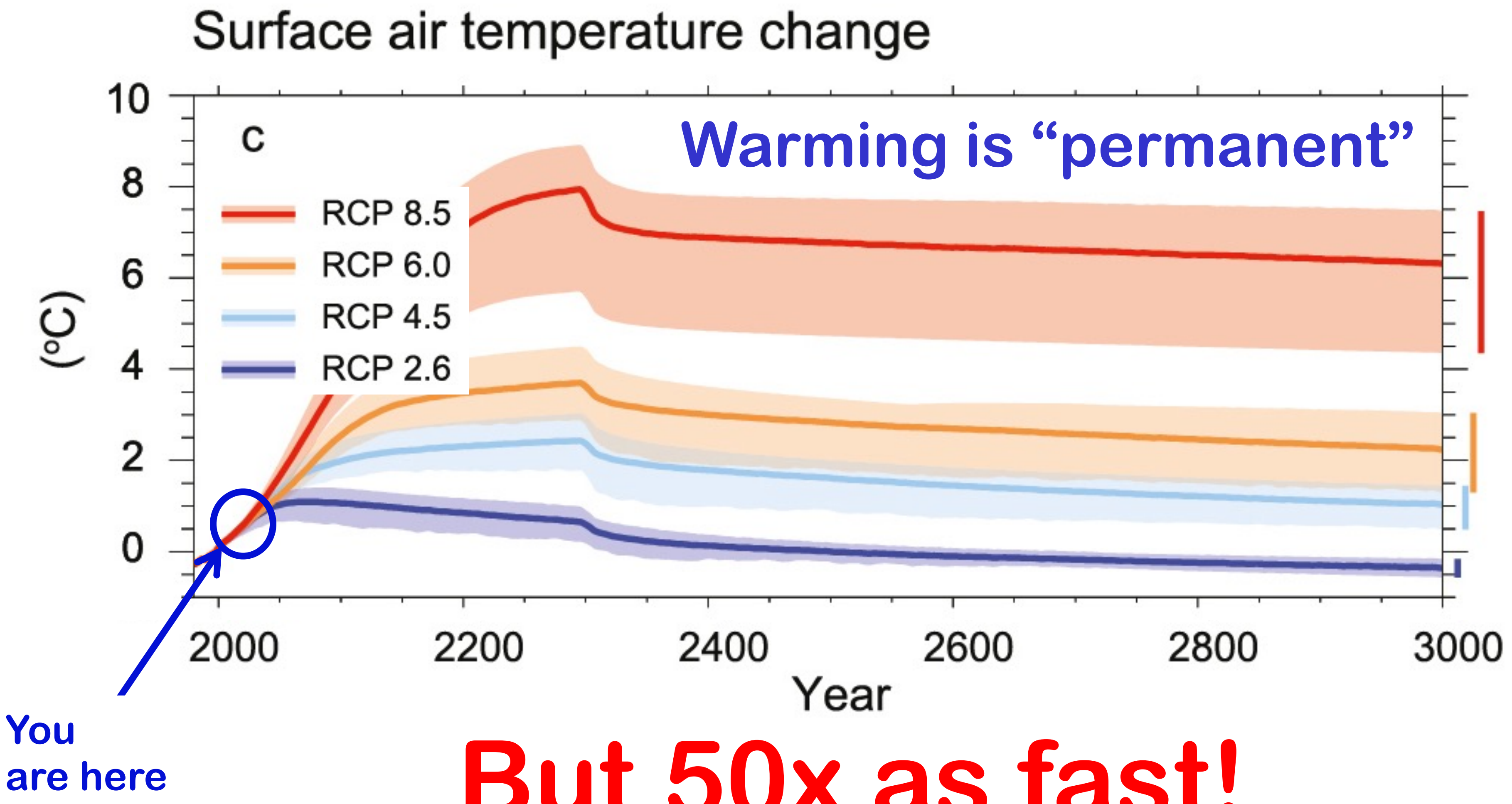


- Fossil CO_2 dissolves into the oceans
- Chemistry limits the amount the oceans can hold
- Mixing with deep oceans is very slow
- Removal of CO_2 depends on how much we add to atmosphere
- For a big pulse, 40% is still in the air after 1000 years



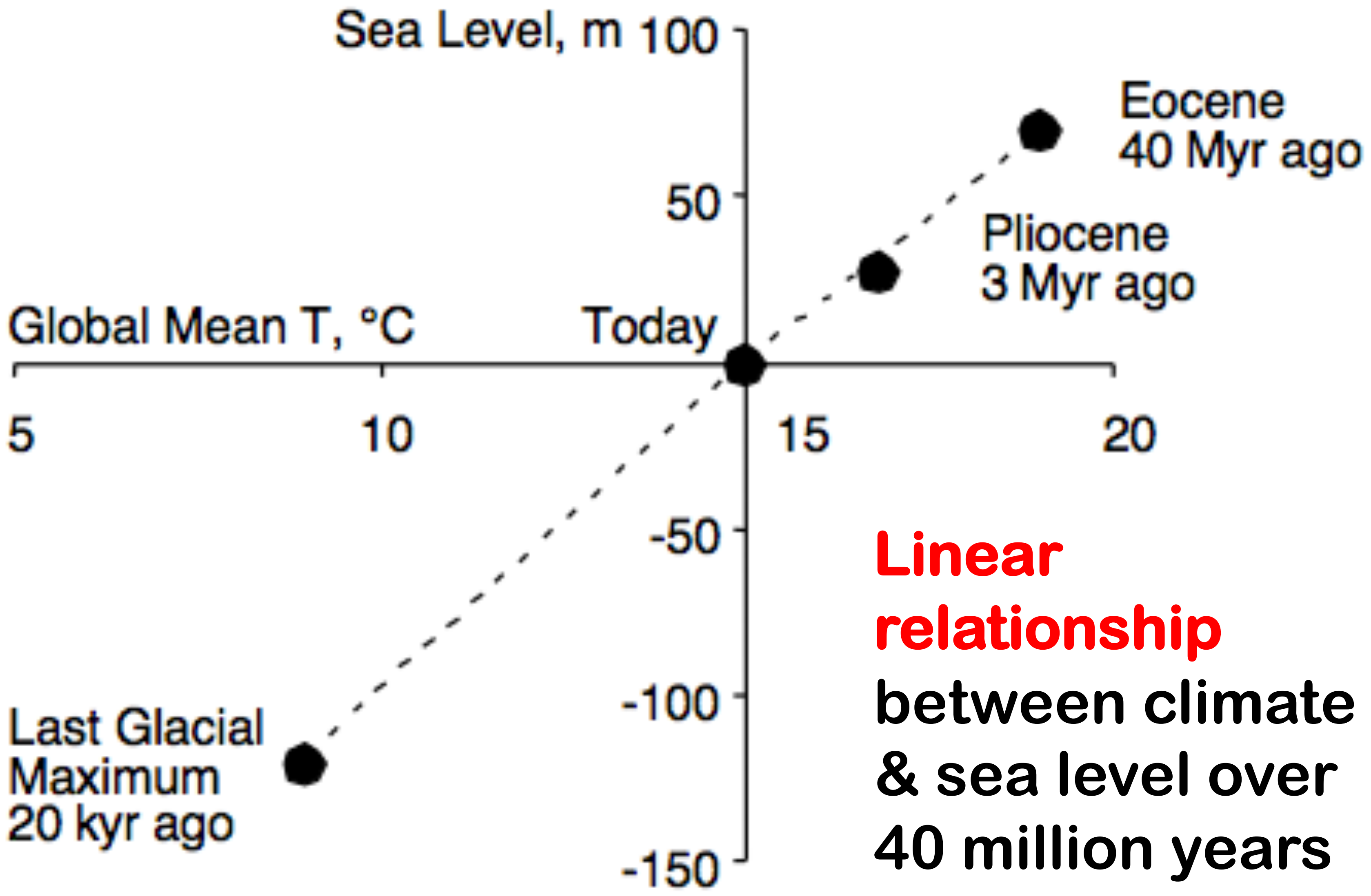
CO2 emissions
2000
2200
2400
2600
2800
3000
a
Emissions peak soon
30
20
10
0
(PgC yr-1)
RCP 8.5
RCP 6.0
RCP 4.5
RCP 2.6
Zero emissions from 2300 for all scenarios
Atmospheric CO2
2000
1500
1000
500
b
(ppmv)
CO2 Lasts Much Longer
1500 ppm in 3000 AD!

Bigger than Deglaciation



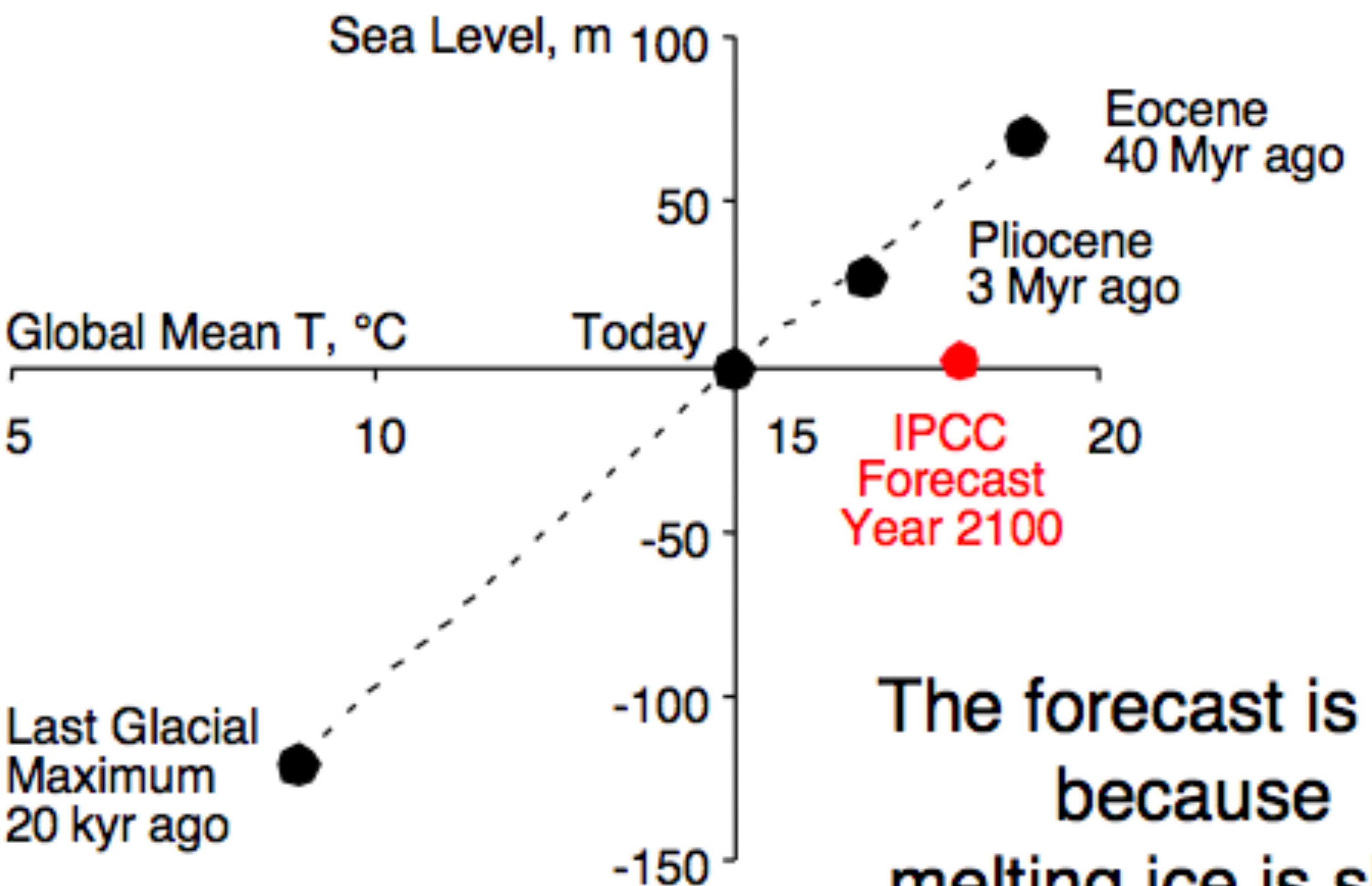
But 50x as fast!

Climate and Sea Level



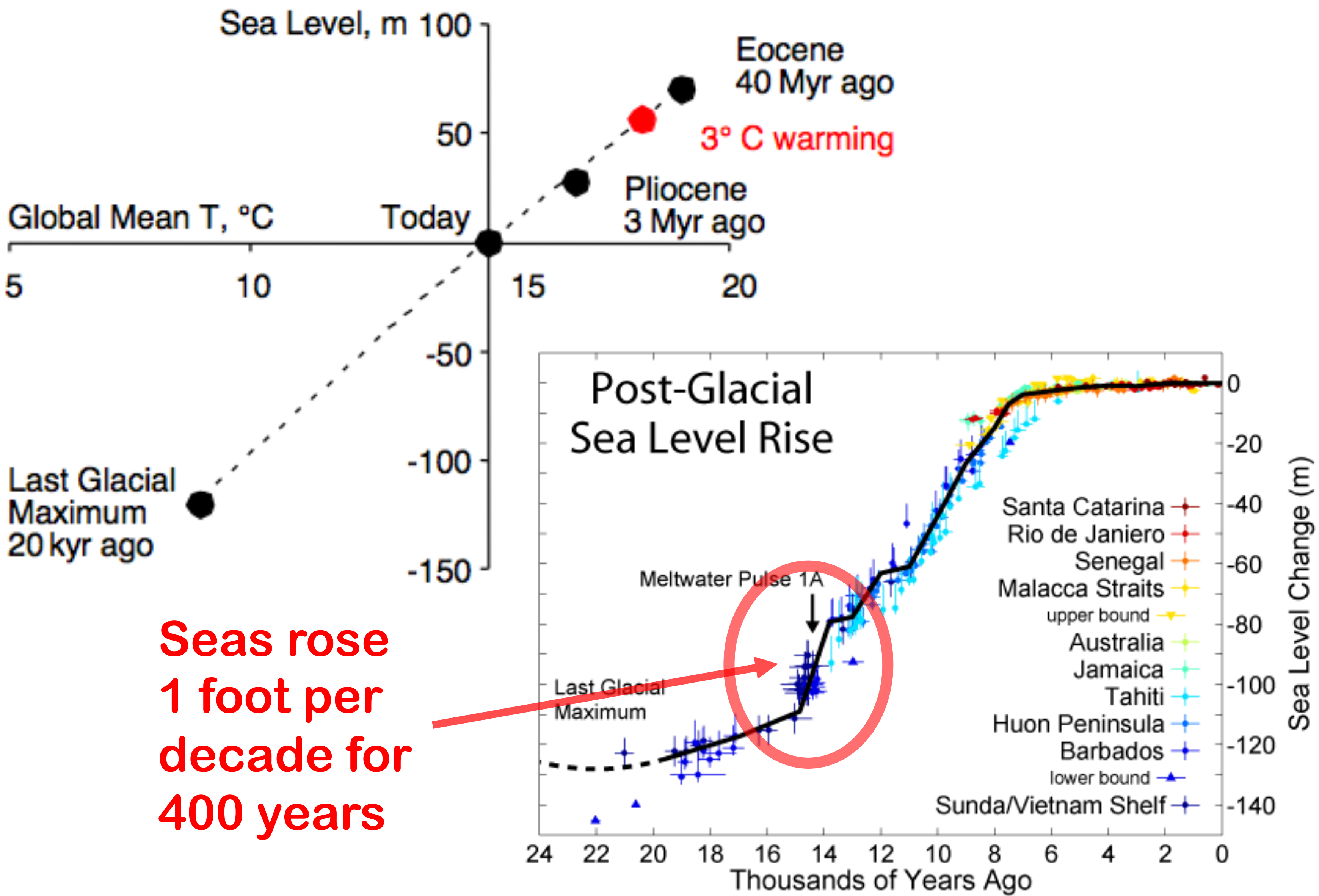
Linear relationship between climate & sea level over 40 million years

Climate and Sea Level



The forecast is low because melting ice is slow.

Climate and Sea Level



Seas rose 1 foot per decade for 400 years

Eventually

http://www.freetech4teachers.com/2013/09/an-interactive-map-of-rising-sea-levels.html